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TECHNOLOGY INCORPORATED Final Report

Contract No. F41609-67-C-0040

PREPARED FOR:

USAF School of Aerospace Medicine
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FOREWORD

This report was prepared by the following personnel of the Life Sciences Division of Technology Incorporated:

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ABSTRACT

Time and wavelength dependent mathematical models for retinal burns and for flashblindness from nuclear detonations are developed in this report. These models are incorporated into a computer program with the latest weapon and burn threshold data to calculate safe separation distances as a function of time for given sets of initial conditions. The results, which present safe separation envelopes with time as a parameter, are included in the appendices. Yield, altitude of detonation, visibility and day or night conditions are also parameters. Retinal burn predictions with this model compare favorably with the experimental results obtained during Operation Dominic.

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I. INTRODUCTION

It has been known for many years that damage to the eyes can occur as a result of viewing a very bright light, and the development of nuclear warfare introduced a new and potentially more hazardous light source capable of producing eye injuries (retinal burns). Further, it was recognized that, due to the focusing of energy by the eye, injury could be sustained at extremely long distances--much greater distances, in fact, than those at which injury could be produced by any other direct effects. Even though permanent injury may not always be produced, a temporary impairment of visual function (flashblindness) can be experienced that could seriously affect an individual's ability to carry out critical tasks. The potential effect on military operations dictated the need for a thorough study of the problems and the development of methods to predict "safe" distances of approach with respect to these two effects.

The purposes of this report are (1) to present consistent and general time and wavelength dependent mathematical models for the prediction of retinal burns and flashblindness and (2) to incorporate these models, along with the latest and most complete threshold and source data available, in an efficient and flexible computer program which will determine the distances of closest approach (or safe separation distances) for specific situations.

With respect to retinal burns, the safe separation distance is defined as the minimum horizontal range from fireball to observer (measured along the earth's surface) that will prevent the observer from sustaining permanent eye damage before protective action, such as a blink, can occur. In the case of flashblindness the safe separation distance is the minimum horizontal distance from fireball to observer (measured along the earth's surface) that will enable the observer to recover the ability to perform a specified visual task within 10 seconds of the initiation of the flash.

II. VISUAL EFFECTS

A. Retinal Burns

When a fireball is viewed, the light rays received by the eye are refracted by the cornea, lens, and ocular media and focused on the retina forming there an image of the fireball. The light energy is absorbed in the retina and adjacent structures, producing a region of elevated temperature. If the temperatures generated exceed the biological tolerances, permanent injury will result with an associated permanent loss of visual function in the region affected. Present research efforts are attempting to delineate threshold temperatures, but relatively little reliable quantitative information is available. Lack of knowledge of threshold temperatures

necessitates the continued use of threshold criteria based upon visual observations of retinal changes in laboratory animals as a function of retinal exposure and an extrapolation of these results to humans.

Visual impairment due to a retinal burn will depend on the size, severity and location of the burn. Two factors, the fireball diameter and the distance from fireball to observer, determine the image size; however, the burn size is a function of the severity of the burn as well as the size of the image. The location of the burn is also an important factor in considering the effects of retinal burns. For example, a large burn in the fovea would seriously affect visual acuity. However, a burn in the periphery would have much less effect on visual acuity and would probably result only in a "blind spot" that may or may not produce annoying consequences. Bilateral burns that include the central 2.5° field would reduce visual acuity to about 57 per cent of normal and could seriously affect the observer's ability to function properly. It should be emphasized that retinal burns can result in some impairment of vision in the form of "blind spots" and reduced visual acuity, but complete visual incapacitation is exceedingly unlikely.

B. Flashblindness

It has been conclusively demonstrated that flashblindness, i.e.,

the temporary loss of visual sensitivity following exposure to a high luminance stimulus, can be produced by viewing a nuclear fireball. The high-luminance flash forms an afterimage of the same relative size and shape as the source and is perceived as a bright or dark area (depending on the luminance of the background) in the visual field. Initially, the brightness of the afterimage is related to the amount of photo-pigment bleached in the retinal image area. Critical detail that could be detected prior to the flash is usually lost against this bright area for a period following the flash. In order for the critical detail of a test object to be seen "through" the afterimage, the object must produce a primary image of sufficient brightness to create detectable contrasts. The time between the flash exposure and the time that the observer can distinguish critical detail is called the recovery time and is a measure of the effects produced by the disturbance.

The general form of recovery time curves as a function of flash energy, assuming a constant flash duration, is shown in Figure 1.[1] Test object luminance is the parameter between curves. There will be no significant effect on visual function if the stimulus energy is very low. As stimulus energy is increased, an increase in recovery time is noted, but for exposures beyond those at which maximum bleaching occurs, recovery times may change very little

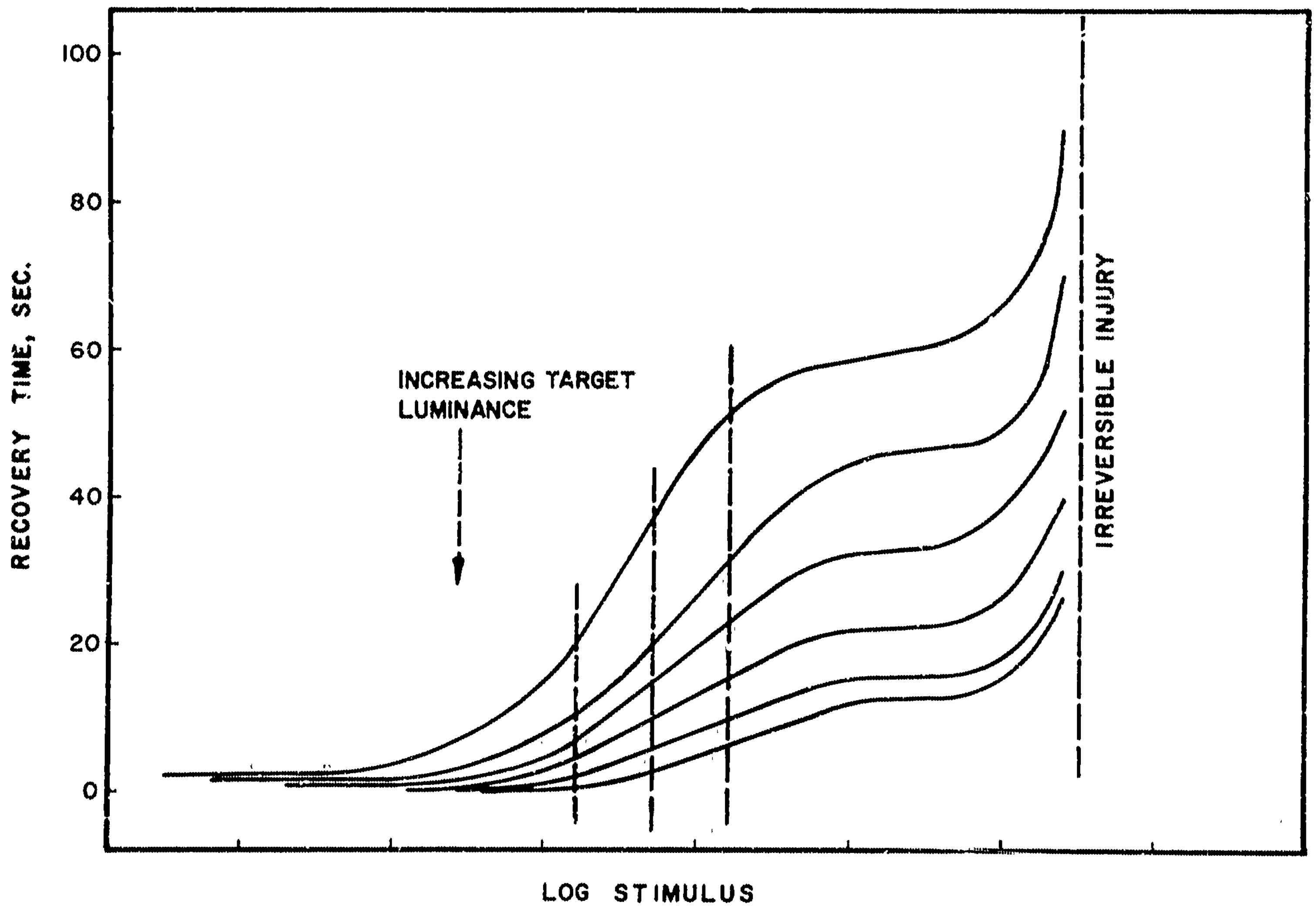

FIGURE 1. Effect of flash energy and target luminance on flashblindness recovery time

with an increase in stimulus energy. However, as the flash energy approaches the threshold for injury, recovery time increases rapidly until permanent injury occurs.

Test object luminance is an important variable in determining recovery times. The nature of the relationship between test object luminance and recovery time can be seen from Figure 1. Note that for increasing test object (target) luminances, recovery times decrease. Therefore, recovery time is a function of the integrated luminous energy in the flash, background lighting conditions and the luminance and critical detail of the test object used to determine recovery.[2]

III. MATHEMATICAL MODEL AND PREDICTION TECHNIQUES

A. Retinal Burns

Whether or not an observer will receive a retinal burn depends upon whether or not the retinal radiant exposure (Q_r) exceeds the threshold exposure (Q_c). Thus, the problem of calculating a safe separation distance is simply that of determining the distance at which $Q_r = Q_c$. The procedure for calculating these two quantities follows.

1. Determination of Q_r

The first problem is the computation of the "source term", i.e., the power output of the weapon as a function of time and wavelength for any yield. Spectral power is given by

$$P_\lambda = a(\lambda, t^*)\, W^{b(\lambda, t^*)} \qquad (1)$$

where

W = yield (kilotons)

P_λ = spectral power $\left(\frac{\text{cal}}{\text{sec-}\mu}\right)$

$t^* = \frac{t(\text{sec})}{t_{2max}} = \frac{t(\text{sec})}{0.037W^{0.47}} \left(\frac{\rho_o}{\rho_H}\right)^{0.282}$

and is called the scaled time.

t = real time after onset of pulse (sec)

$t_{2max} = 0.037W^{0.47}\left(\frac{\rho_H}{\rho_o}\right)^{0.282}$

ρ_o = density of atmosphere at sea level

ρ_H = density of atmosphere at burst height

The coefficients $a(\lambda, t^*)$ and the exponents $b(\lambda, t^*)$ reflect Operation Dominic experience (Project 4.1) and have been compiled for 10 discrete wavelength bands. It should be noted that the altitude dependence of the power term has been taken into account by the inclusion of the atmospheric density factor in the expression for scaled time.[3] As the burst height of a given weapon increases,

the scaled time also increases; this corresponds to the fact that the real time required to release a specified amount of energy decreases with increasing altitude.

Because the computer program uses spectral radiance, N_λ, instead of spectral power, it is necessary to calculate the fireball diameter, FD, as a function of time, yield, and burst height. Experimental fireball data as well as theoretical computations were used in deriving the following scaling relationship:

$$FD(t^*, W)\,(cm) = 21.350\, FR_s(t^*) W^{0.35} \left(\frac{\rho_o}{\rho_H}\right)^{0.13} \tag{2}$$

where

$FD(t^*, W)$ = actual fireball diameter in cm at scaled time t^* and yield W.

$FR_s(t^*)$ = scaled fireball radius in cm determined from experiments.

This expression should be reasonably valid over the range of yields and burst altitudes considered in this report.

With spectral power, P_{λ_i}, and fireball diameter, $FD(t^*)$, determined, the spectral radiance, N_{λ_i}, is computed as follows:

$$N_{\lambda_i}(W, \lambda_i, t_j^*) \left(\frac{\text{cal.}}{\text{cm}^2\text{-sec-}\mu\text{-}\Omega}\right) = \frac{P_{\lambda_i}(W, \lambda_i, t_j^*)}{\left[\pi\, FD(t_j^*)\right]^2} \tag{3}$$

Retinal irradiance is calculated for all times of interest, t_j^*, at a given horizontal range, S:

$$H_r(t_j^*, S)\left(\frac{\text{cal.}}{\text{cm}^2\text{-sec}}\right) = \frac{\pi}{4}\left(\frac{PD}{FL}\right)^2 \sum_{i=1}^{10} N_{\lambda i}(W, \lambda_i, t_j^*)\, T(\lambda_i, D)\Delta\lambda_i \tag{4}$$

where

PD = pupil diameter of the human eye (night: 5.5 mm, day: 2.5 mm)

FL = effective focal length of the human eye, 17 mm

$T(\lambda_i, D)$ = the transmission through a distance D of the atmosphere plus that of any canopies or filters, and the ocular media for the spectral band centered at λ_i

D = slant range, cm

$\Delta\lambda_i$ = band width of the ith spectral band, μ

From the retinal irradiance at t_{j-1}^*, and that at t_j^*, the retinal radiant exposure for the time increment $\Delta t_j = (t_j^* - t_{j-1}^*)\, t_{2max}$ is determined, i.e.,

$$\Delta Q_{r_j}\left(\frac{\text{cal}}{\text{cm}^2}\right) = \frac{H_r(t_j^*, S) + H_r(t_{j-1}^*, S)}{2}\ \Delta t_j \tag{5}$$

Obviously then, the total retinal exposure up to time t_j^* is

$$Q_{r_j}\left(\frac{\text{cal}}{\text{cm}^2}\right) = \sum_{i=1}^{j} \Delta Q_{r_i}(t_i^*, S) \tag{6}$$

Equation 6 completes the determination of the retinal exposure as a function of distance and time. The problem of calculating

$T(\lambda_i, D)$, however, remains. As noted above, the total transmission is composed of three parts: transmission through the atmosphere from fireball to observer, transmission through any canopies or filters, and transmission through the ocular media of the subject being considered.

Spectral transmission values for the ocular media of the human were obtained from Boettner and Wolter.[4] It is assumed that no filters will be present to obstruct vision and that the spectral transmission values for an aircraft window taken from the Dominic project report are representative for aircraft windshields[5].

Narrow beam transmission through the atmosphere is assumed and this simplified model includes only scattering by air and water vapor. No account is taken of water vapor absorption and the effects of dust or other contaminants. Thus, transmission through this simplified atmosphere is given by

$$T_a(\lambda_i, D) = \left[T_{air}(\lambda_i)\right]^{AM} \left[T_{H_2O}(\lambda_i)\right]^{W} \tag{7}$$

where

$T_{air}(\lambda_i)$ = transmission for pure dry air for one gram per square centimeter in the spectral band centered at wavelength λ_i

$T_{H_2O}(\lambda_i)$ = transmission for one precipitable centimeter of water vapor (one gram per square centimeter) in the spectral band centered at wavelength λ_i

AM = number of grams per square centimeter of air in the direct path from fireball to observer

W = number of precipitable centimeters (grams per square centimeter) of water vapor in the direct path from fireball to observer

$T_a(\lambda_i, D)$ = total atmospheric transmission in the spectral band centered at wavelength λ_i for the direct path between the fireball and the observer

$T_{air}(\lambda_i)$ and $T_{H_2O}(\lambda_i)$ are taken from Smithsonian Meteorological Tables.[6] In order to calculate AM and W, an integration along the slant path is made for the air and the water vapor density. That is,

$$AM \left(\frac{gm}{cm^2}\right) = \int_D \rho(h)dl \tag{8}$$

$$W \left(\frac{gm}{cm^2}\right) = \int_D WVDe^{-(WLR)(h)}dl \tag{9}$$

where

$\rho(h)$ - density of the atmosphere $\left(\frac{gm}{cm^3}\right)$ as a function of altitude, h (km)[7]

dl = element of slant path between detonation and observer in centimeters

WVD = water vapor density at sea level[5] $= 0.000022 \ \frac{gm}{cm^3}$

WLR = water vapor density lapse rate[5] $= 0.5397 \ \frac{1}{km}$

Figure 2 illustrates the quantities involved in the integration procedure. The program takes note of the sphericity of the earth and precludes the calculation of a separation distance that would lie beyond the horizon.

To calculate safe separation distances for a prescribed atmospheric visibility, the constants WVD and WLR in the equation for water vapor density as a function of altitude are modified. For a 10 km visibility, WVD is given a value which will reduce the sea level transmission to two per cent at 10 km. WLR is given a value such that the modified water vapor density is equal to the unmodified water vapor density when the two are compared at an altitude of five miles.

2. Determination of Q_c

The determination of the appropriate Q_c is accomplished using the burn threshold values measured by Technology Incorporated under Contract AF41(609)-3099.[8] The measured burn thresholds (measured using rabbits) have been fitted with the expression:

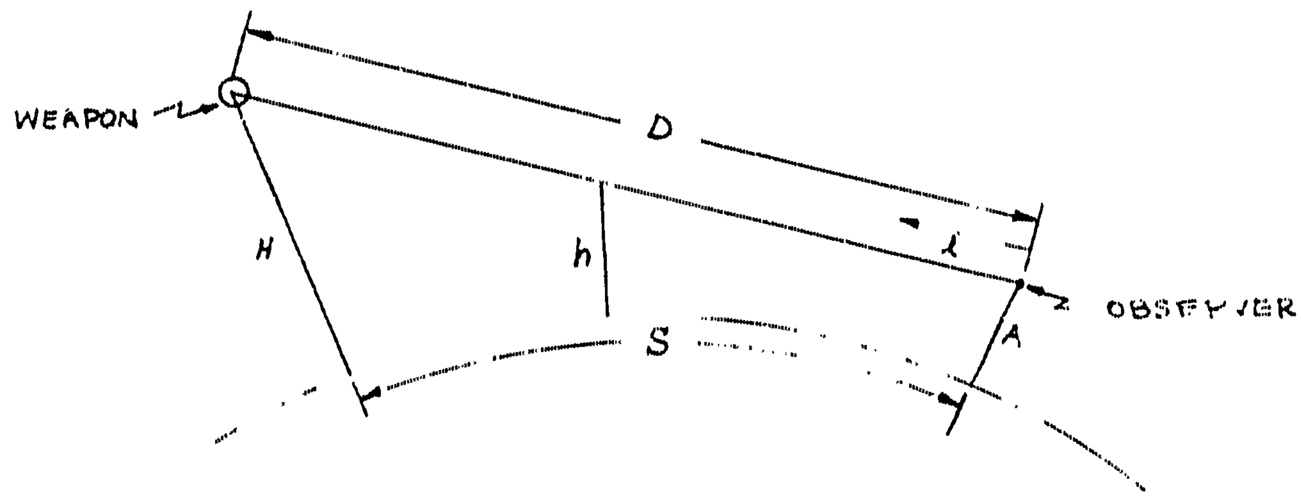

FIGURE 2. Geometry for Calculation of Atmospheric Transmission

$$Q_c \left(\frac{cal}{cm^2}\right) = \left[P_o(t) d_i^{-2} + H_o(t)\right] t \qquad (10)$$

where

d_i (mm) = image diameter

and $P_o(t)$ and $H_o(t)$ are known tabular functions.

Figure 3 shows the resulting curves for exposure times between 10^{-4} and 10 seconds. However, the difference between the way the laboratory threshold exposures were made and the way exposures from nuclear weapons occur necessitates careful consideration when comparisons are made.

At low altitudes, the fireball exhibits a typical two pulse behavior; unfortunately the laboratory threshold exposure data were taken with single square pulse exposures. Thus, actual field data (with a continuously varying irradiance) and the laboratory data (with a constant irradiance) are not directly comparable. This is further complicated by the fact that the image increases in size with time in the case of a nuclear exposure, whereas the laboratory measurements were made with fixed size images.

The approach used here is to approximate the actual exposure during time t, with an exposure calculated as if it occurred under conditions similar to those in the laboratory; i.e., fixed size square pulse exposure. This is accomplished by determining an

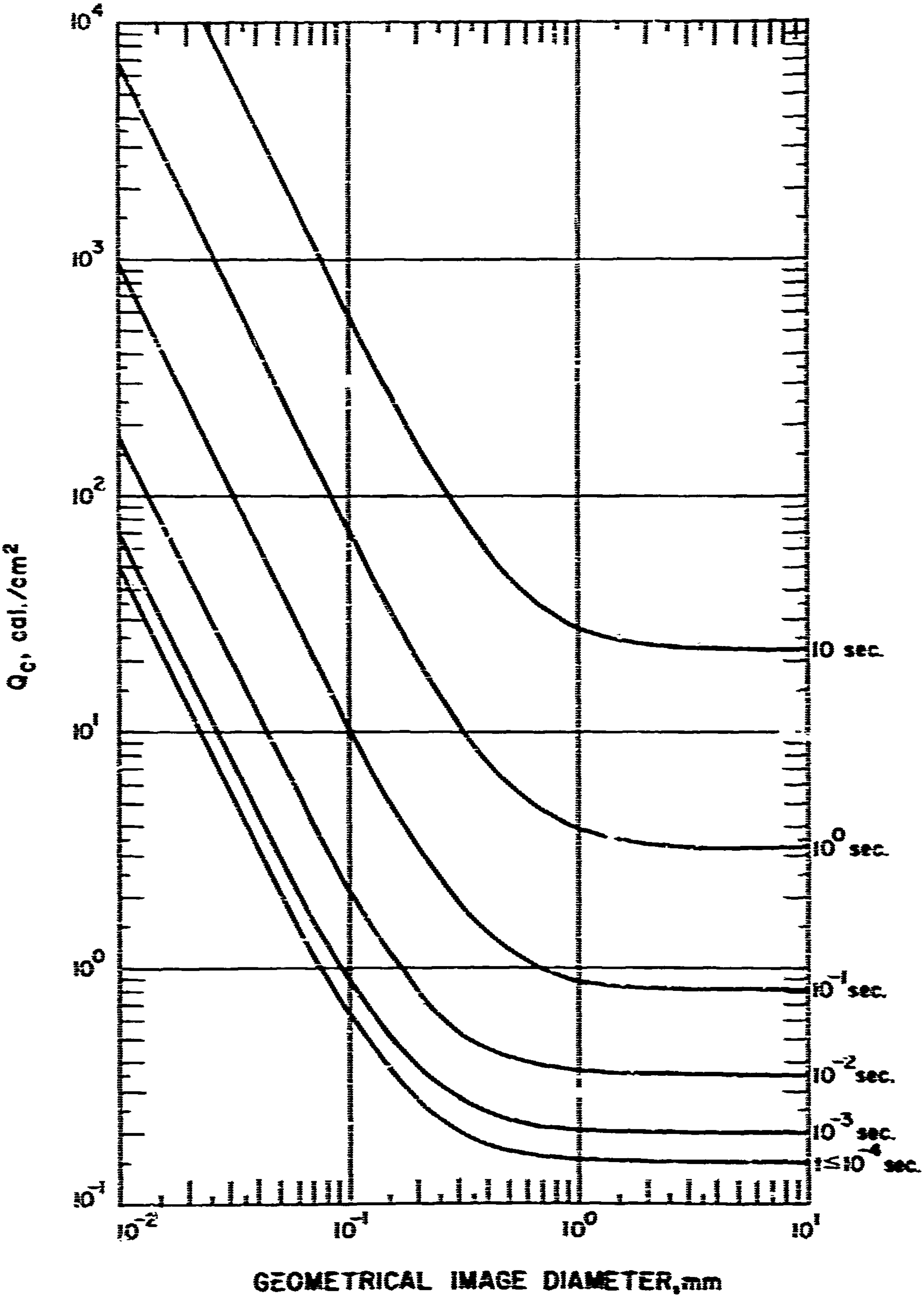

Figure 3. Threshold retinal exposure for rabbits as a function of geometrical image diameter and exposure time.

effective image diameter (d_i^{eff}) during the exposure time t and by assuming that the entire exposure occurs at the maximum retinal irradiance (H_r^{max}) experienced up to time t. In order to conserve the total retinal exposure (Q_r) an effective exposure time (t^{eff}) is established with the relationship:

$$t^{eff} = \frac{Q_r}{H_r^{max}} \qquad (11)$$

The effective exposure time is calculated for each cumulative time and is used in Equation 10 for the critical exposure Q_c. Because the total energy in the first pulse is less than one per cent of the total energy in the second pulse, the calculation of t^{eff} is begun anew at the second pulse; i.e., Q_r is set equal to zero and any previous value of H_r is neglected.

The effective image diameter during the time t is established by weighting the actual image area as a function of time with the retinal irradiance (H_r). This places most emphasis on the image diameters that exist when the irradiance is greatest. The weighting is done conserving energy (ε_r) on the retina and assumes a uniform irradiance across the image:

$$\varepsilon_r = A^{eff} \int_t H_r(t)dt = A^{eff} Q_r(t) = \int_t A(t)H_r(t)dt \qquad (12)$$

where

$$A(t) = \frac{\pi}{4} \left[d_i(t)\right]^2 = \text{area of the retinal image}$$

$$A^{eff} = \frac{\pi}{4} \left[d_i^{eff}\right]^2 = \text{area of the effective retinal image for the time } t$$

$Q_r(t)$ = total retinal exposure at the center of the image for the time t

Upon rearrangement, the following expression is obtained for the effective image diameter:

$$d_i^{eff} = \left[\frac{\int_t \left[d_i(t)\right]^2 H_r(t)dt}{Q_r} \right]^{\frac{1}{2}} \tag{13}$$

Upon substituting the effective exposure time and the effective image diameter into Equation 10, the following equation is obtained:

$$Q_c\left(\frac{cal}{cm^2}\right) = \left[P_o(t^{eff}) \left(d_i^{eff}\right)^{-2} + H_o(t^{eff})\right] \quad t^{eff} \tag{14}$$

Equations 6 and 14 complete the calculation of the retinal exposure and threshold exposure. However, a safety factor of 2 is applied to Q_r to account for inadequacies in the source data as well as approximations in the method. A safety factor of 4 is also applied to Q_r to compensate for the fact that: one, the threshold data were obtained for burns appearing within five minutes after exposure on

rabbits and minimal burns could appear at still later times; and, two, that the human fovea is assumed to be more sensitive than the rabbit eye which has no fovea. With these safety factors included, the equation to be solved for the safe separation distance is $8Q_r = Q_c$. Sample safe separation envelopes are presented in Figure 4. Figure 5 shows the results of tests for retinal burn on rabbits during Operation Dominic. Also shown are burn threshold distances predicted with the present model for the rabbit and safe separation distances for man with the safety factor of 8.

B. <u>Flashblindness</u>

In order to ascertain whether an observer in a given situation will be "flashblinded" for more than an acceptable period of time, it is necessary to consider three factors. These three factors are the image diameter, the direct-image exposure, and the extra-image exposure. Preliminary evidence by Richey[9] indicates that imperative visual information can be extracted from a typical aircraft instrument panel following exposure to a centrally fixated flash of light, provided the image subtends a visual angle less than 3°. In view of this result, a focused image on the fovea of less than 0.9 millimeters (0.9 millimeters corresponds to a 3° visual angle) is considered to have no significant effect on the observer's ability to

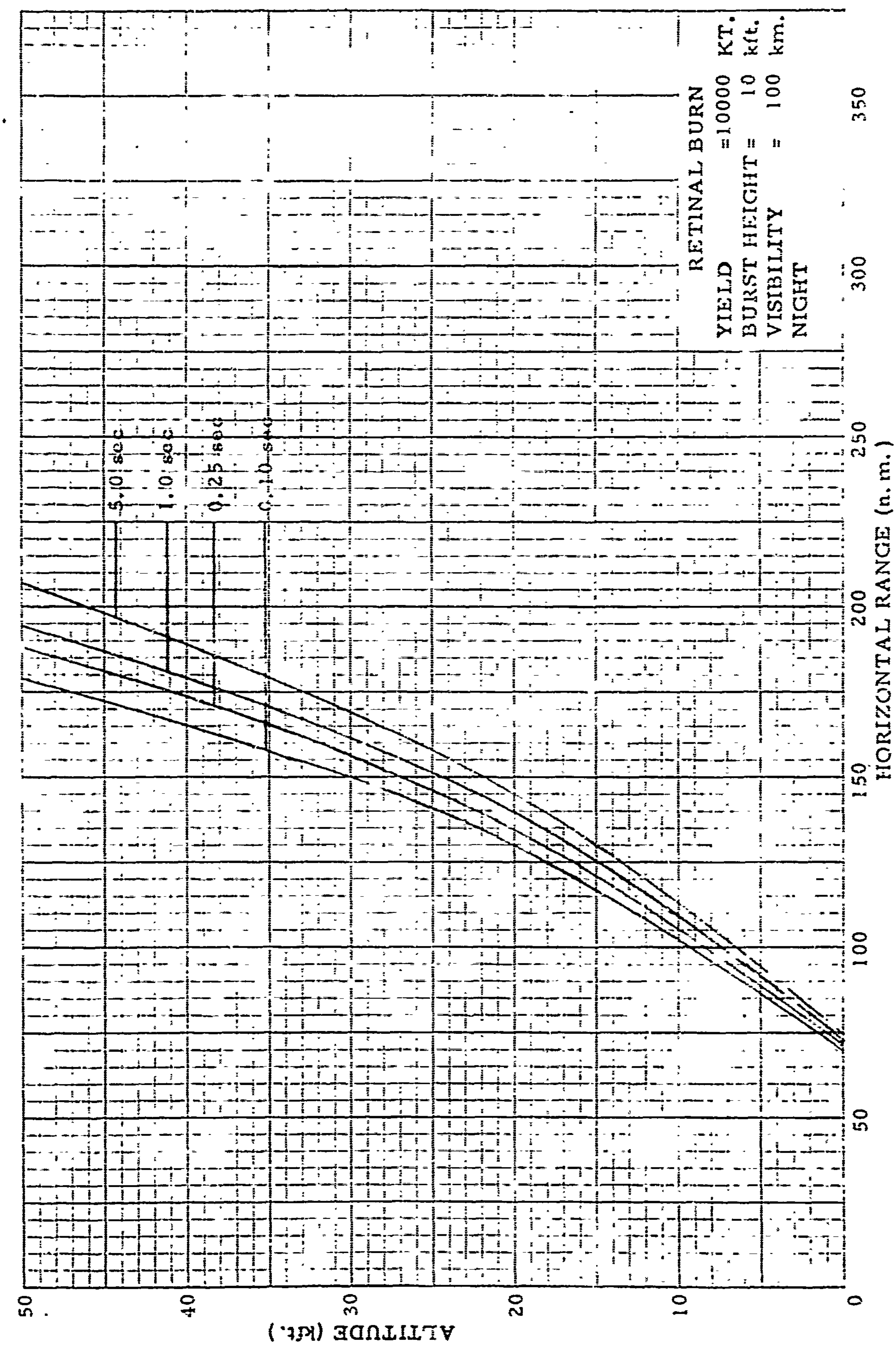

Figure 4. Example of retinal burn safe separation distance

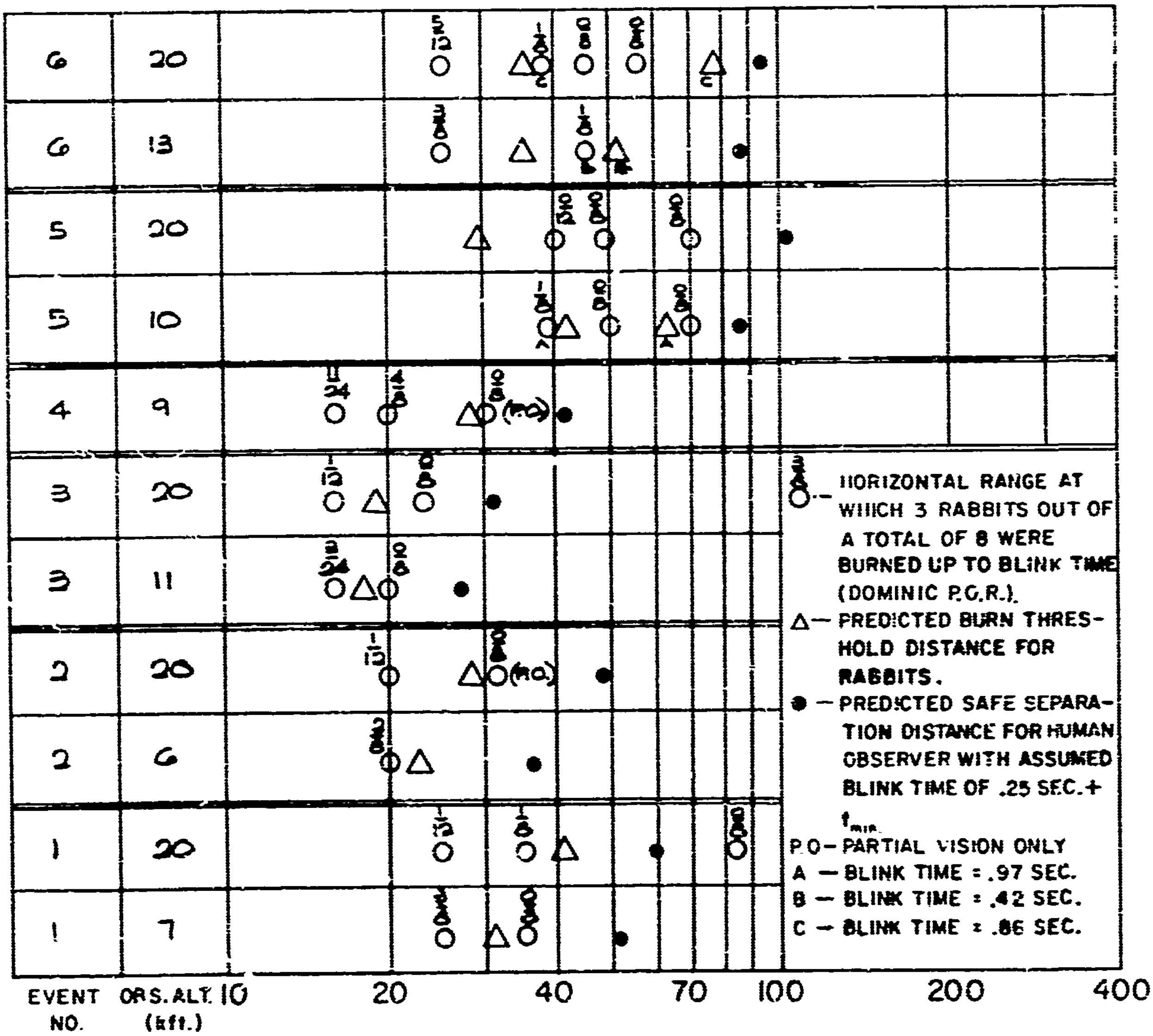

Figure 5. Operation Dominic burn threshold distances for rabbits and predicted safe separation distances for man.

perform this kind of visual task. Therefore, the calculation of a safe separation distance for flashblindness is essentially reduced to one of finding the horizontal range at which the retinal exposure, E_r ($trol_{eff}$-sec), either direct or extra-image at 1.5° from the fovea, is equal to the threshold retinal exposure, E_c ($trol_{eff}$-sec). The determination of E_r (with the assumption that the image is centered on the fovea--a worst case philosophy) and E_c is explained in the following sections.

1. Determination of E_r

Since the direct- and extra-image exposures are essentially products of different mechanisms, they will be dealt with separately in this section. The direct-image exposure will be calculated first.

Direct image retinal exposure, E_r^d($trol_{eff}$-sec) at a time t_k and at a horizontal range S is equal to the product of the time-integrated luminance of the source $\left(\frac{cd\text{-}sec}{m^2}\right)$ and the effective area of the observer's pupil (mm^2); i.e.,

$$E_r^d\,(trol_{eff}\text{-sec}) = \frac{\pi}{4}(PD_{eff})^2 \sum_{j=1}^{k} \sum_{i=1}^{10} L_{\lambda_i}(\lambda_i, t_j^*)\,T_{ax}(\lambda_i, D)\,\Delta\lambda_i\,\Delta t_j \tag{15}$$

where

$L_{\lambda_i}(\lambda_i, t_j^*)$ = spectral luminance of the fireball in $\frac{cd}{m^2\text{-}u}$ at time t_j^* and for the bandwidth centered at λ_i

$T_{ax}(\lambda_i, D)$ = transmission through the atmosphere from source to observer and the transmission through any canopies or filters

PD_{eff} = effective pupil diameter (mm)

An effective pupil diameter is used because of the Stiles-Crawford effect and is calculated from the empirical formula[10]

$$PD_{eff}^2 (mm^2) = PD^2 \left[1.0 - 0.085 \frac{PD^2}{8} + 0.002 \frac{PD^4}{48} \right] \tag{16}$$

Spectral luminance is the photometric equivalent of spectral radiance and is computed as follows:

$$L_{\lambda_i}(\lambda_i, t_j^*) \left(\frac{cd}{m^2 - \mu} \right) = 4.19 \times 10^4 \times K\, V_{\lambda_i} N_{\lambda_i}(\lambda_i, t_j^*) \tag{17}$$

where

K = maximum (555 mμ) photopic luminous efficiency = $680 \frac{\text{lumens}}{\text{watt}}$

V_{λ_i} = average photopic relative luminous efficiency over the bandwidth $\Delta\lambda_i$ based on a 10^o field of observation. (Commission Internationale de l'Eclairage)

On substituting Equation 17 into Equation 15, the following expression is obtained:

$$E_r^d(\text{trol}_{eff}\text{-sec}) = 2.24 \times 10^7 (PD_{eff})^2 \sum_{j=1}^{k} \sum_{i=1}^{10} V_{\lambda_i} N_{\lambda_i}(\lambda_i, t_j^*) T_{ax}(\lambda_i, D) \Delta\lambda_i \Delta t_j \tag{18}$$

Equation 18 is used for the retinal exposure as long as the image diameter (at time t_k and at distance S) is larger than 0.9 mm. If the image diameter is less than 0.9 mm. the extra-image exposure is calculated.

The extra-image exposure is theoretically attributable to three separate sources: these are the intra-ocular scattering, the atmospheric scattering, and the reflected energy from clouds, ground and water. Because of the extreme range of conditions that can exist in actual situations, no account was taken of the exposure from clouds, ground, water and other reflecting surfaces in the results presented here.

Vos[11, 12] has derived an expression for intra-ocular scattering as well as one for atmospheric scattering based on the following assumptions:

a. the fireball is a point source with respect to the scattered light.

b. the scattered light varies inversely with the square of the distance from fireball to the observer,

c. the extra-image exposure at a point on the retina is dependent upon the angle between that point and the direction of fixation (i.e., the direction of the fireball).

Extra-image retinal exposure, E_o^{ex} (trol$_{eff}$-sec), from the intra-ocular scattering is given by:

$$E_o^{ex}(\text{trol}_{eff}\text{-sec}) = \frac{9.87(PD_{eff})^2}{D^2\,\theta^2} \sum_{j=1}^{k} \sum_{i=1}^{10} (FD_j)^2 L_{\lambda_i}(\lambda_i, t_j^*) T_{ax}(\lambda_i, D) \Delta\lambda_i \Delta t_j \tag{19}$$

while that for atmospheric scattering, E_a^{ex} (trol$_{eff}$-sec) is given by:

$$E_a^{ex}(\text{trol}_{eff}\text{-sec}) = \frac{-9.87(PD_{eff})^2}{D^2\,\theta} \times$$

$$\sum_{j=1}^{k} \sum_{i=1}^{10} (FD_j)^2 L_{\lambda_i}(\lambda_i, t_j^*)\, T_{ax}(\lambda_i, D) \log_e T_a\,(\lambda_i, D) \Delta\lambda_i\, \Delta t_j \tag{20}$$

where

E_o^{ex} = extra-image exposure due to intra-ocular scattering at a time t_k and at a horizontal range S

E_a^{ex} = extra-image exposure due to atmospheric scattering at a time t_k and at a horizontal range S

θ = angle in degrees between the direction of fixation and the direction corresponding to the point at which the extra-image exposure is being calculated

and all other quantities are as previously defined. Equations 18, 19 and 20 are the complete expressions for the direct- and extra-image exposures.

2. Critical Exposure, E_c

The critical exposure for flashblindness calculations is that exposure for which the observer will be unable to perform a specified visual task for 10 seconds. It is evident from Figure 1 that target or task luminance is a highly important variable in the determination of recovery time for a given stimulus. Therefore, a value of task luminance must be selected for both the day and the night conditions before a threshold exposure can be defined. The average instrument luminance under night conditions has been taken as .07 millilamberts[13], whereas that for day conditions is assumed to be 20 millilamberts.[14] According to Miller[13], the foveal exposures corresponding to the above task luminances for 10 second recovery times are 7.87×10^5 trol_{eff}-sec and 1.97×10^7 trol_{eff}-sec, respectively. It should be noted that the transmission through the eye has not been included in the threshold exposures; and so. $T_{ax}(\lambda_i, D)$ does not include the the eye transmission for any flashblindness calculations.

As in the case of retinal burns, safety factors have been introduced into these calculations. A factor of 2 is again included in the calculated exposure values to compensate for possible errors in weapon output data. A factor of 2 is introduced into the threshold value to account for variations among individuals. Thus, the

equation to be solved for "safe" separation for flashblindness is $4E_r = E_c$ where E_r is the luminous exposure at a position 1.5° from the fovea calculated using equations 18 or 19 and 20, whichever is appropriate. Sample safe separation envelopes are presented in Figure 6.

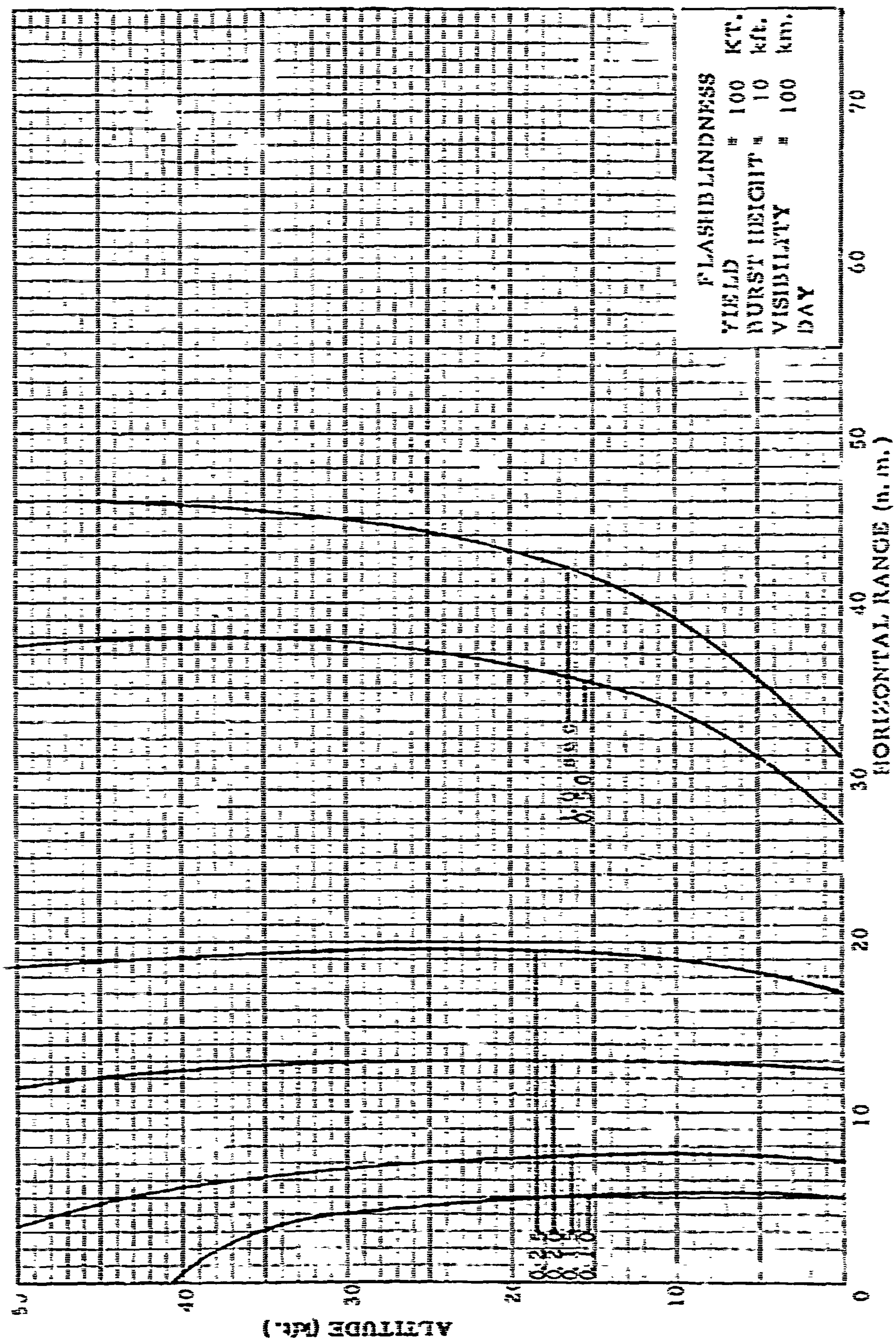

Figure 6. Example of flashblindness safe separation distance.

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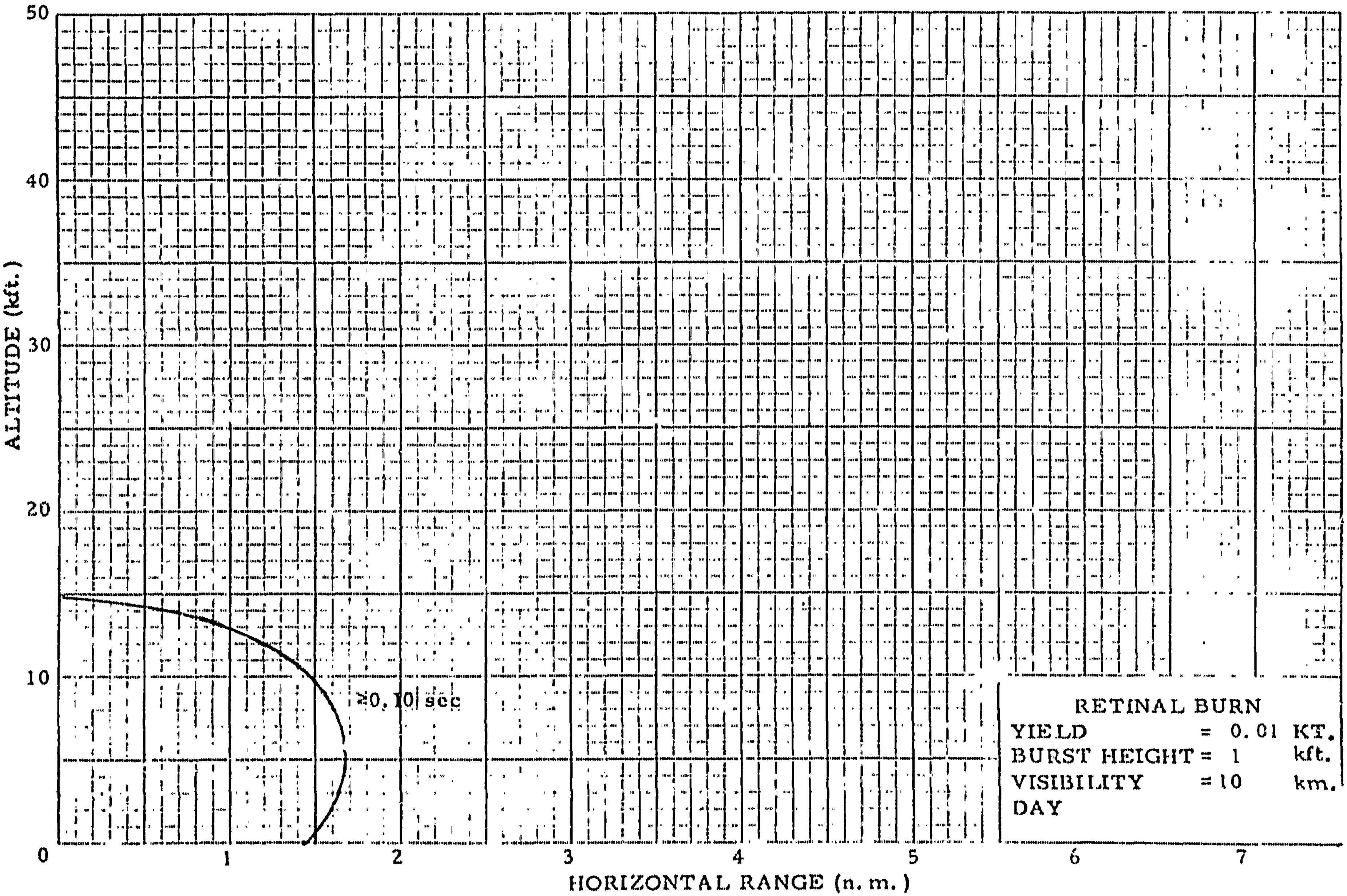
APPENDIX A

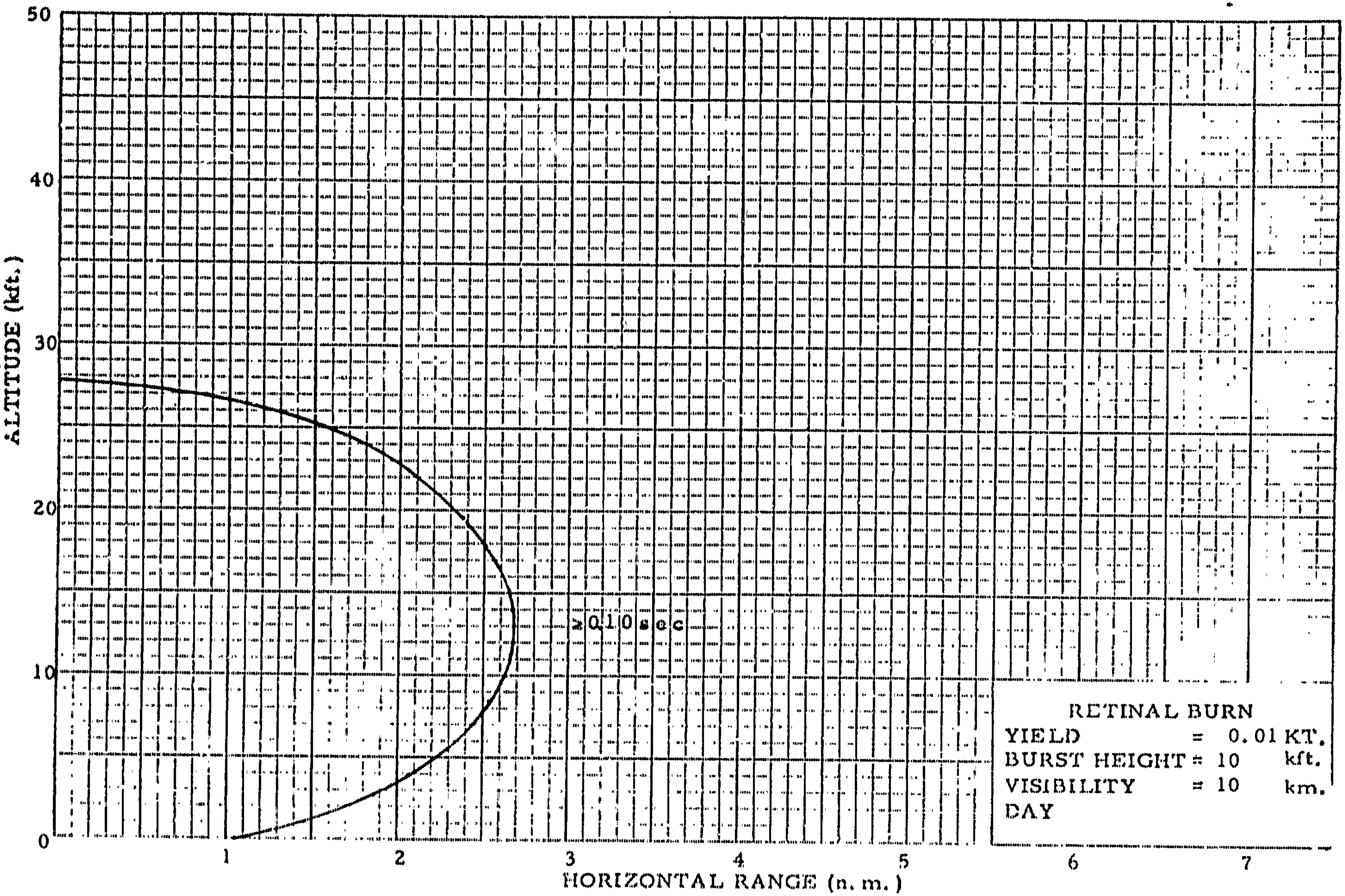
RETINAL BURN SAFE SEPARATION DISTANCE CURVES

RETINAL BURN SAFE SEPARATION DISTANCE CURVES

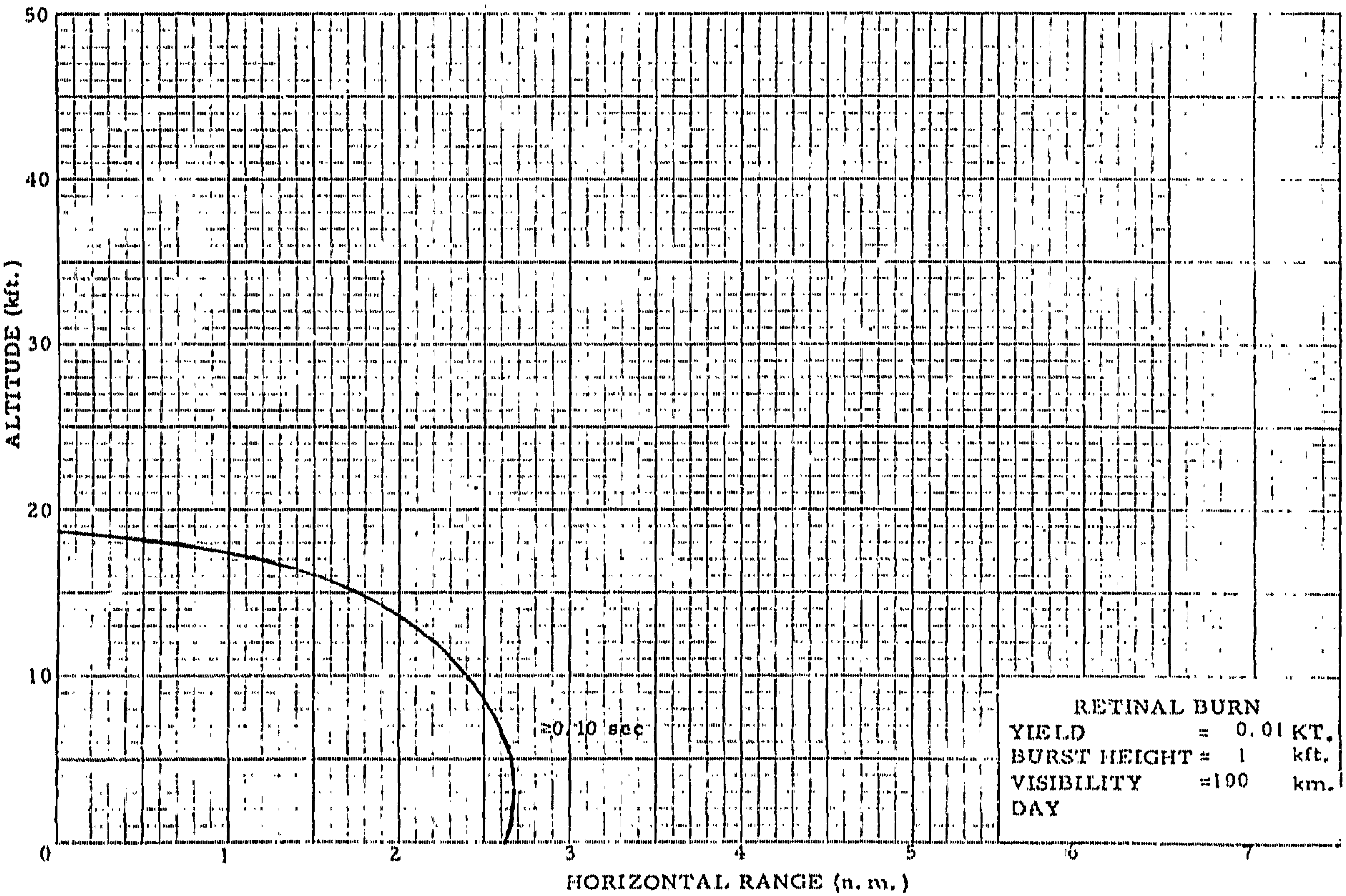
Retinal burn safe separation distances have been calculated by the method described in this report for seven yields (.01, .10, 1.0, 10., 100., 1000., and 10000. KT.), three burst heights (1.0, 10., and 50. kft.), two visibilities (10. and 100. km), and for day and night conditions. The results of these calculations are included in this appendix. Each graph presents safe separation distance as a function of observer altitude for a particular yield, burst height, visibility, and for day or night conditions. Blink time is the parameter between curves, and blink times of .10, .15, .20, .50, 1.0, and 5.0 sec are included in each graph (except where interpolation between times is obvious).

All graphs for day conditions are presented first and followed by those for night conditions. Within these large divisions, the graphs are arranged in order of increasing yield; a further subdivision is made to include increasing visibilities and a final subdivision is made for increasing burst heights. For burst heights of 50 kilofeet, the safe separation distances should be used with caution.

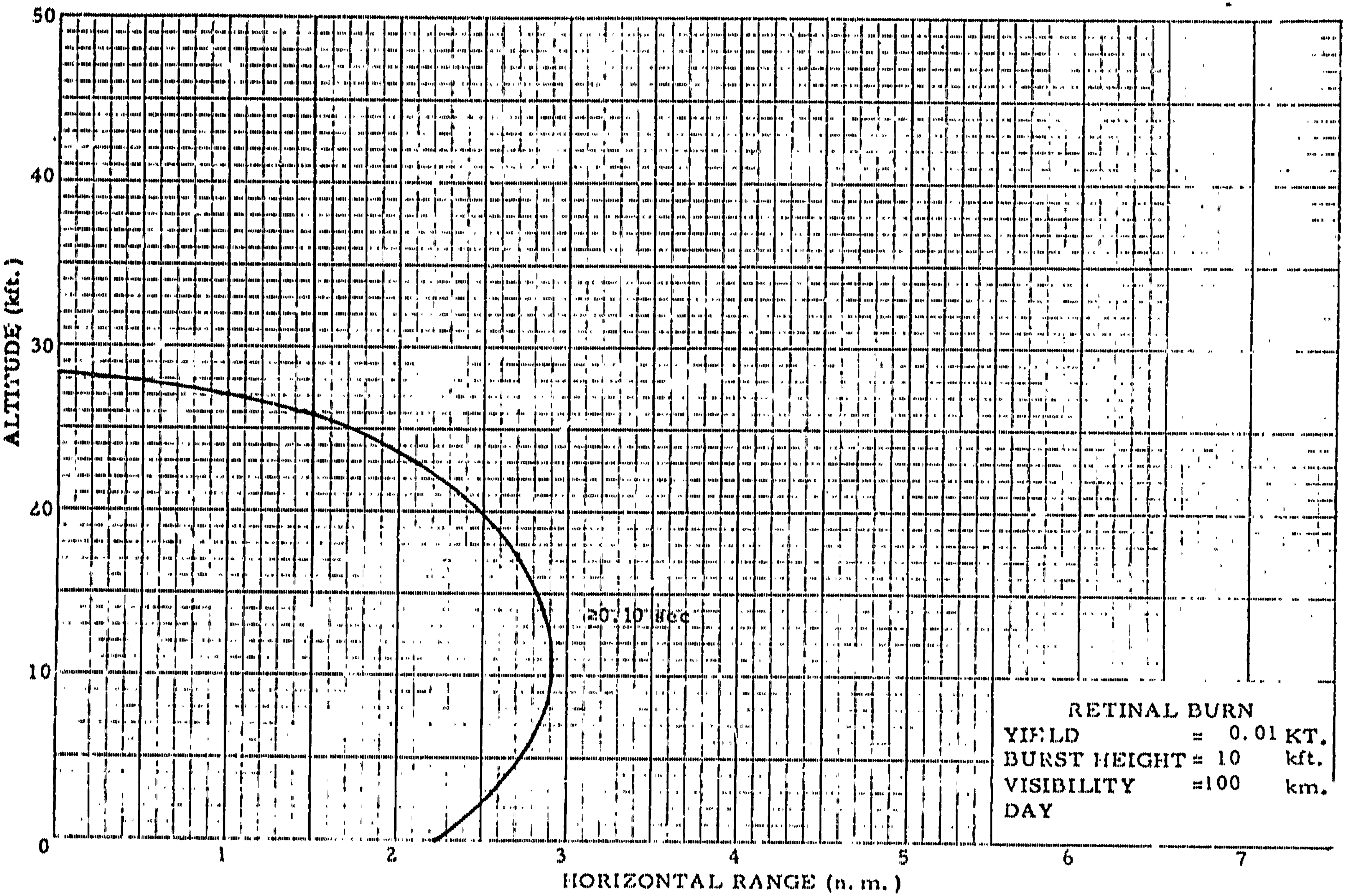

ALTITUDE (kft.)
50
40
30
20
10
0
1
2
3
4
5
6
7
HORIZONTAL RANGE (n. m.)
≥0.10 sec
RETINAL BURN
YIELD = 0.01 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
DAY



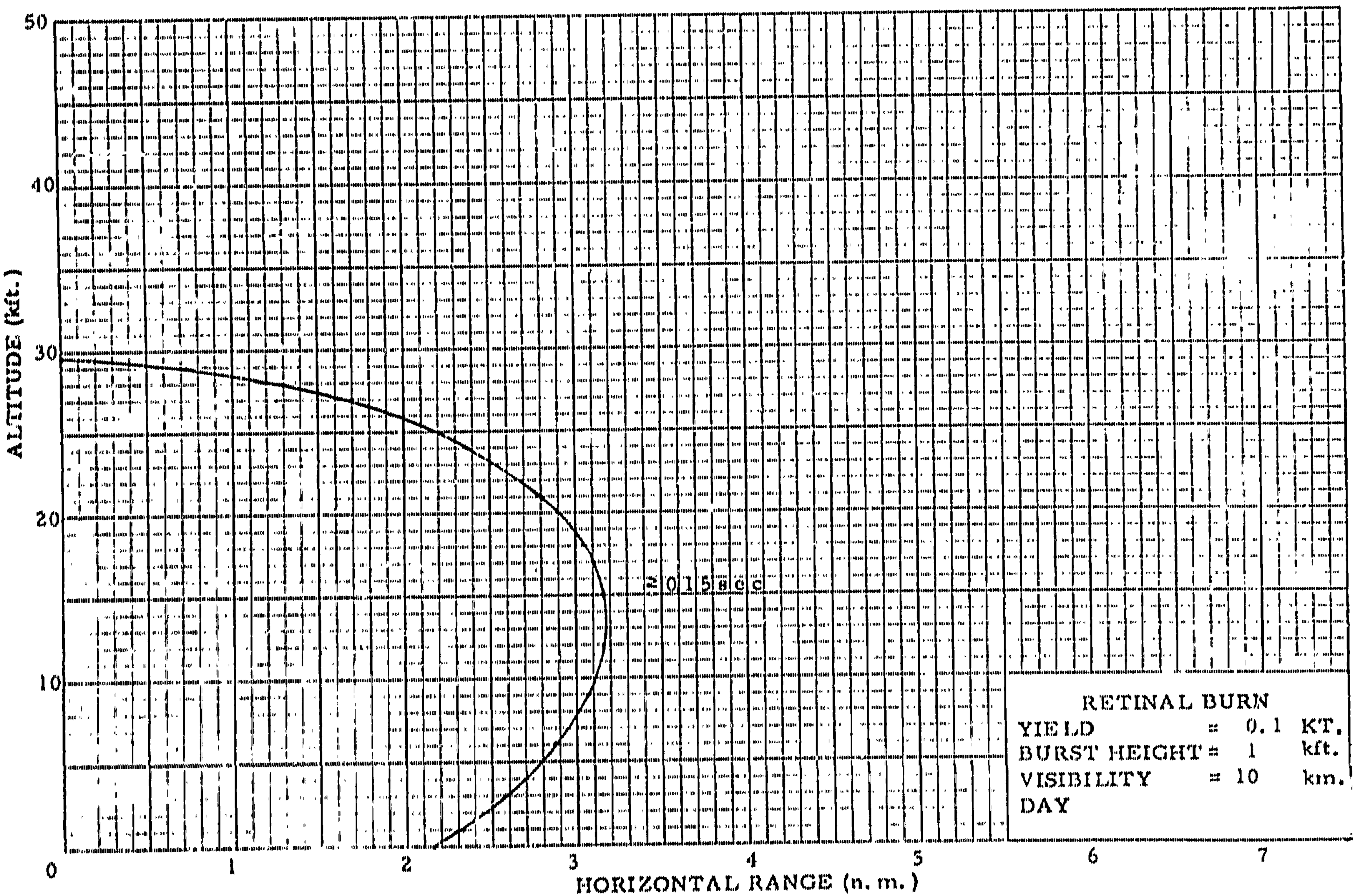
50
40
30
20
10
0
ALTITUDE (kft.)
1
2
3
4
5
6
7
HORIZONTAL RANGE (n. m.)
≥0.10 sec
RETINAL BURN
YIELD = 0.01 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
DAY

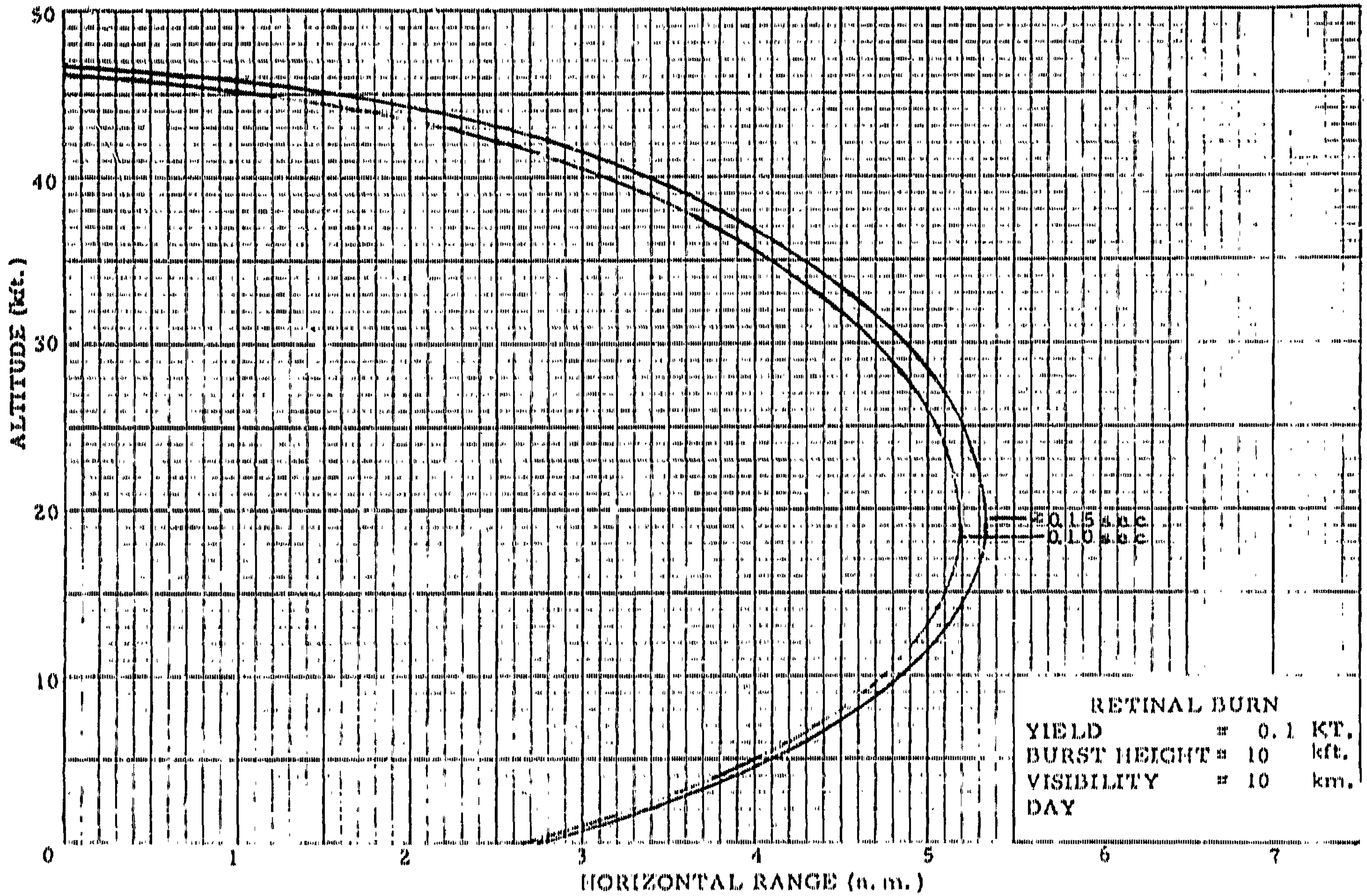


50
40
30
20
10
0
ALTITUDE (kft.)
1
2
3
4
5
6
7
HORIZONTAL RANGE (n. m.)
≥0.10 sec
RETINAL BURN
YIELD = 0.01 KT.
BURST HEIGHT = 1 kft.
VISIBILITY =100 km.
DAY

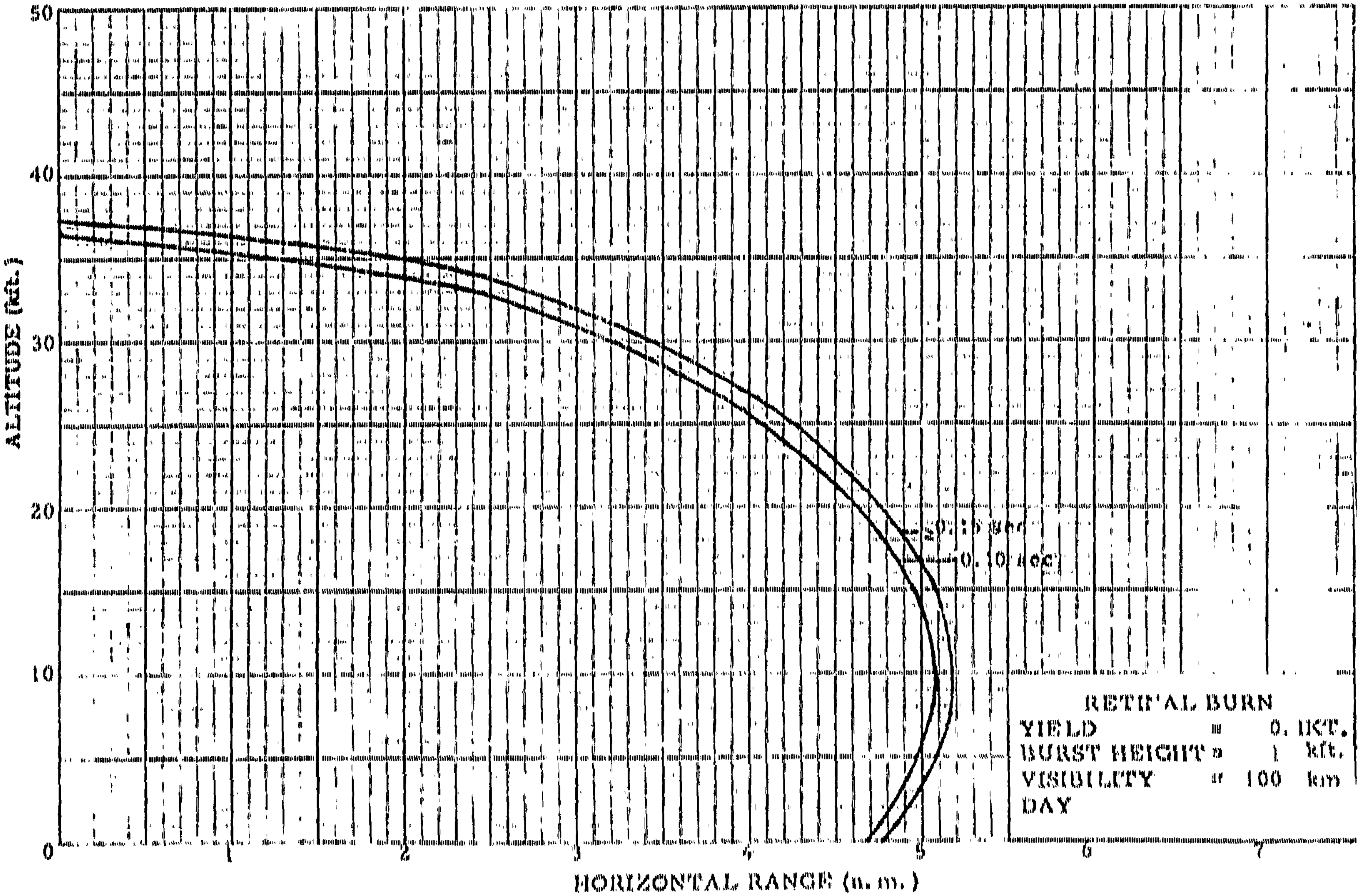


ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n. m.)
1
2
3
4
5
6
7
RETINAL BURN
YIELD = 0.01 KT.
BURST HEIGHT = 10 kft.
VISIBILITY =100 km.
DAY

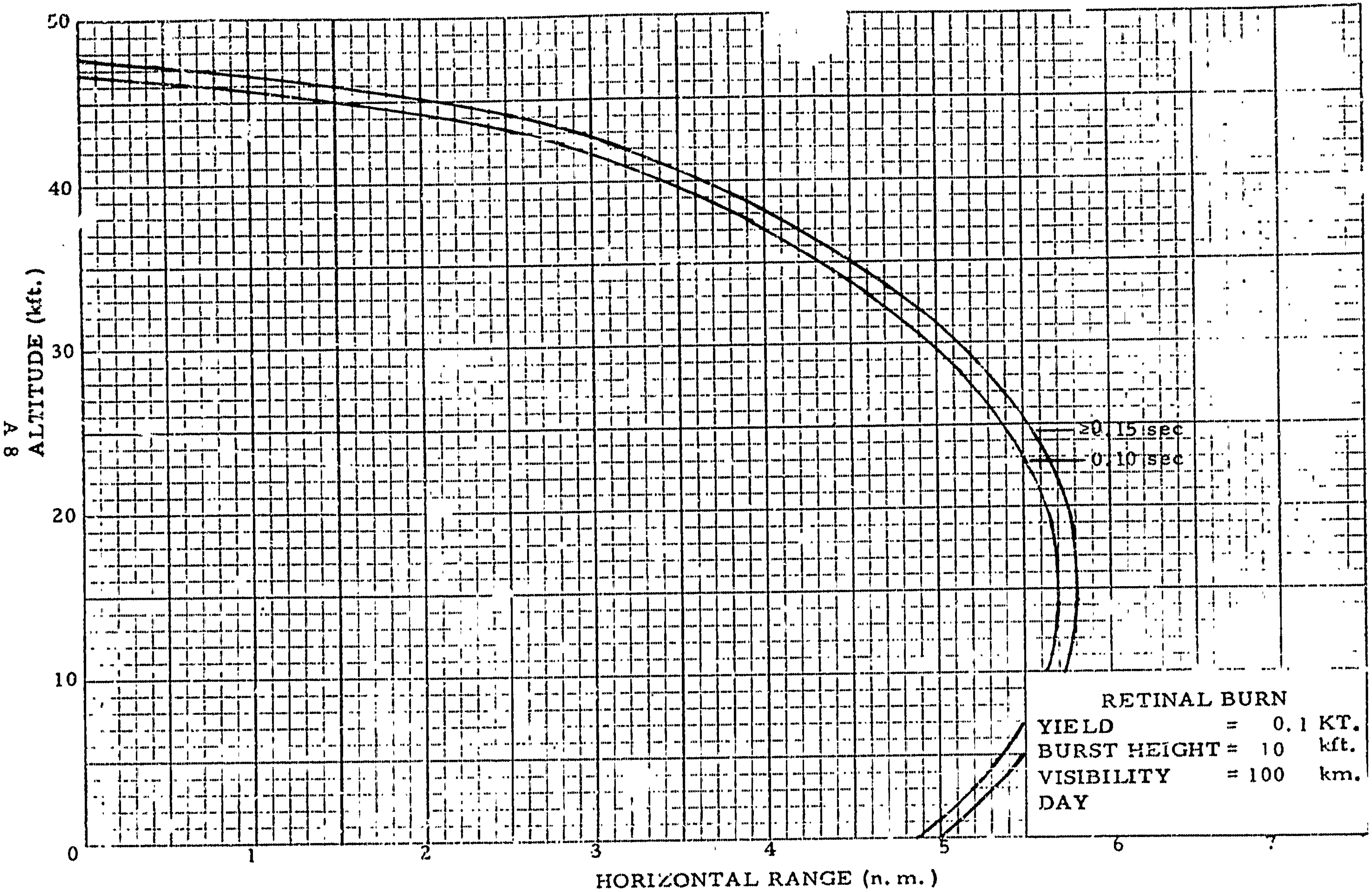

RETINAL BURN
YIELD = 0.1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
1
2
3
4
5
6
7
10
20
30
40
50



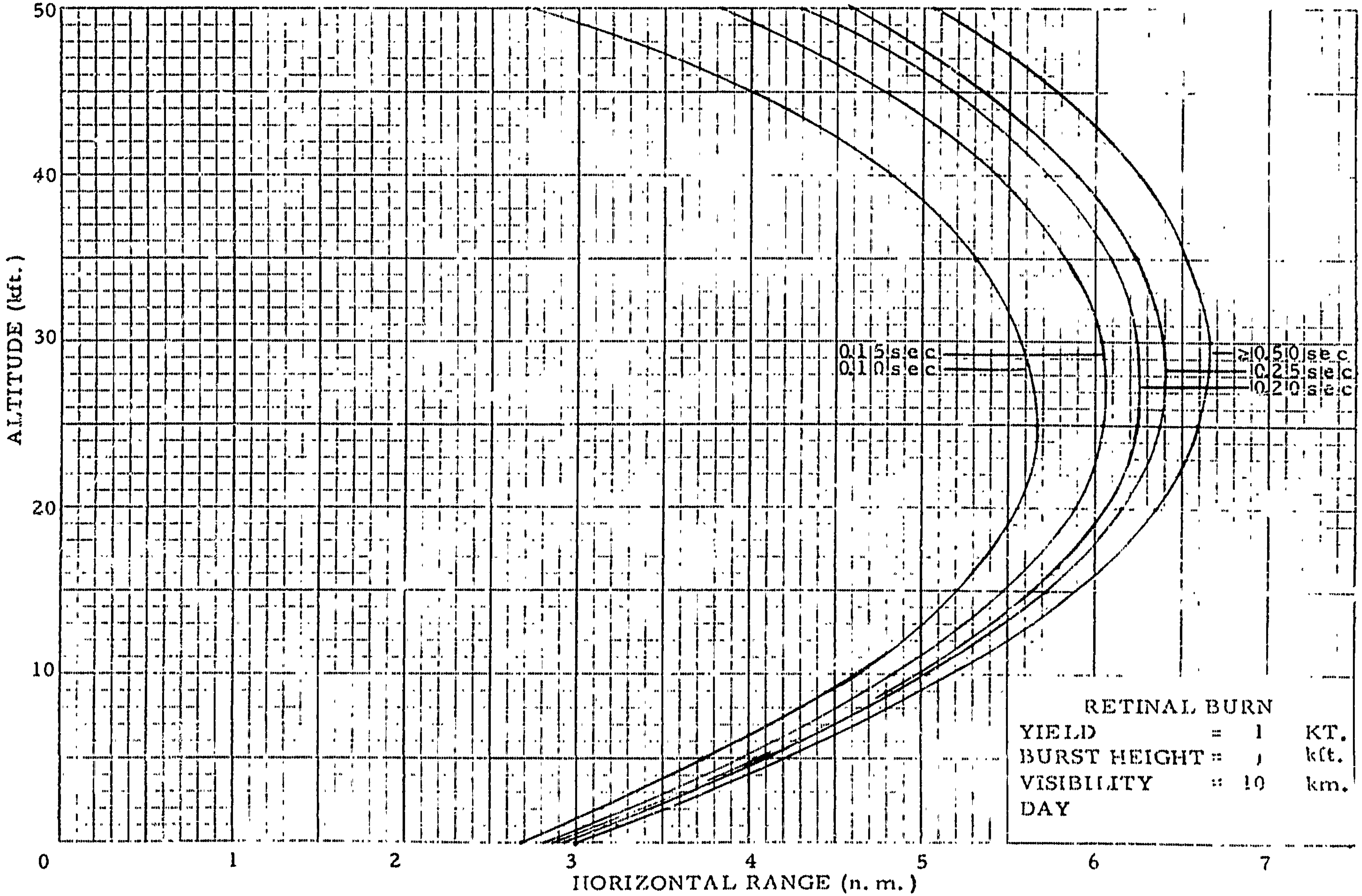
RETINAL BURN
YIELD = 0.1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
DAY
0.15 sec
0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
1
2
3
4
5
6
7

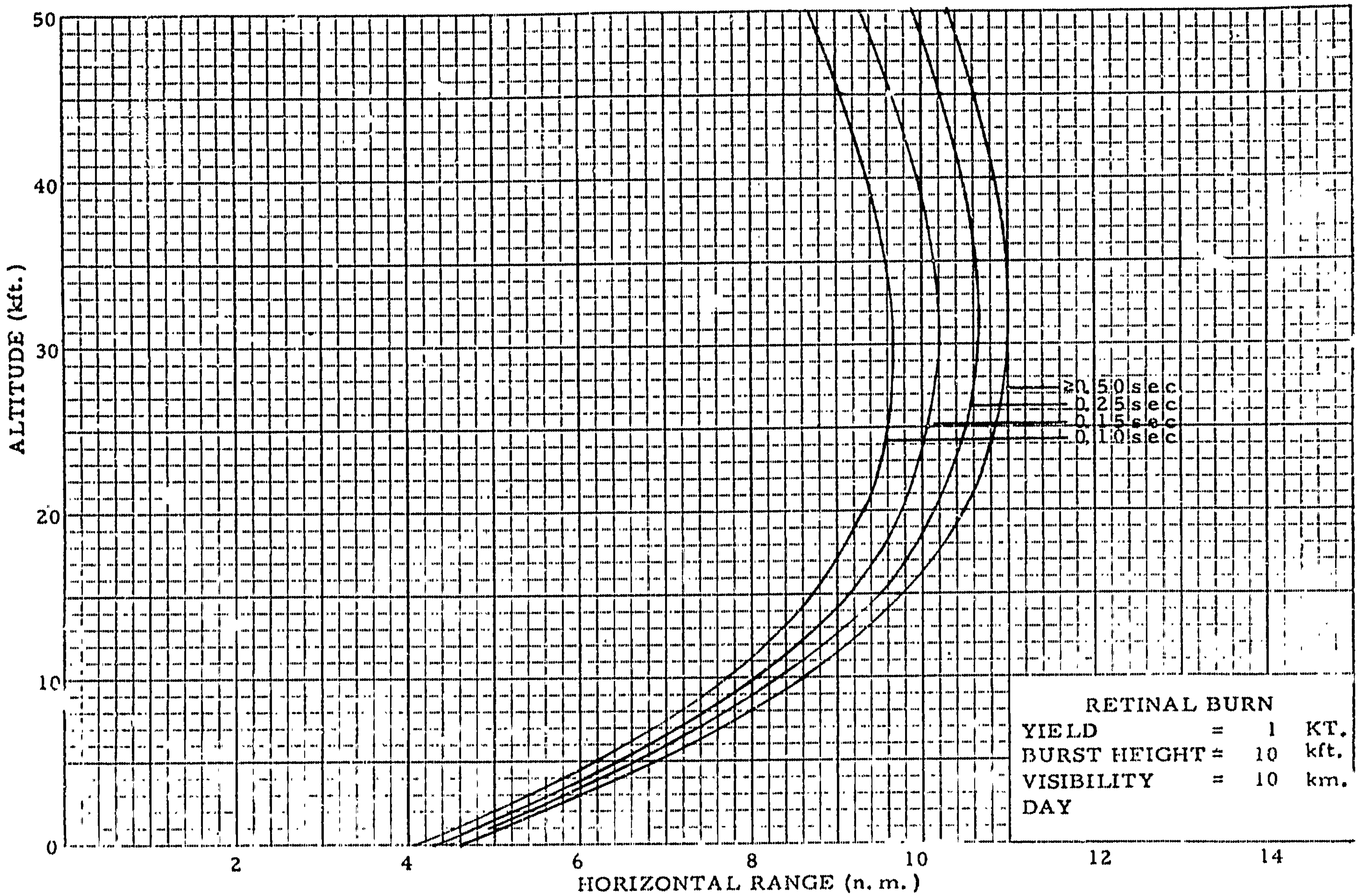

RETINAL BURN
YIELD = 0.1KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km
DAY
0.15 sec
0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n.m.)
0
10
20
30
40
50
1
2
3
4
5
6
7

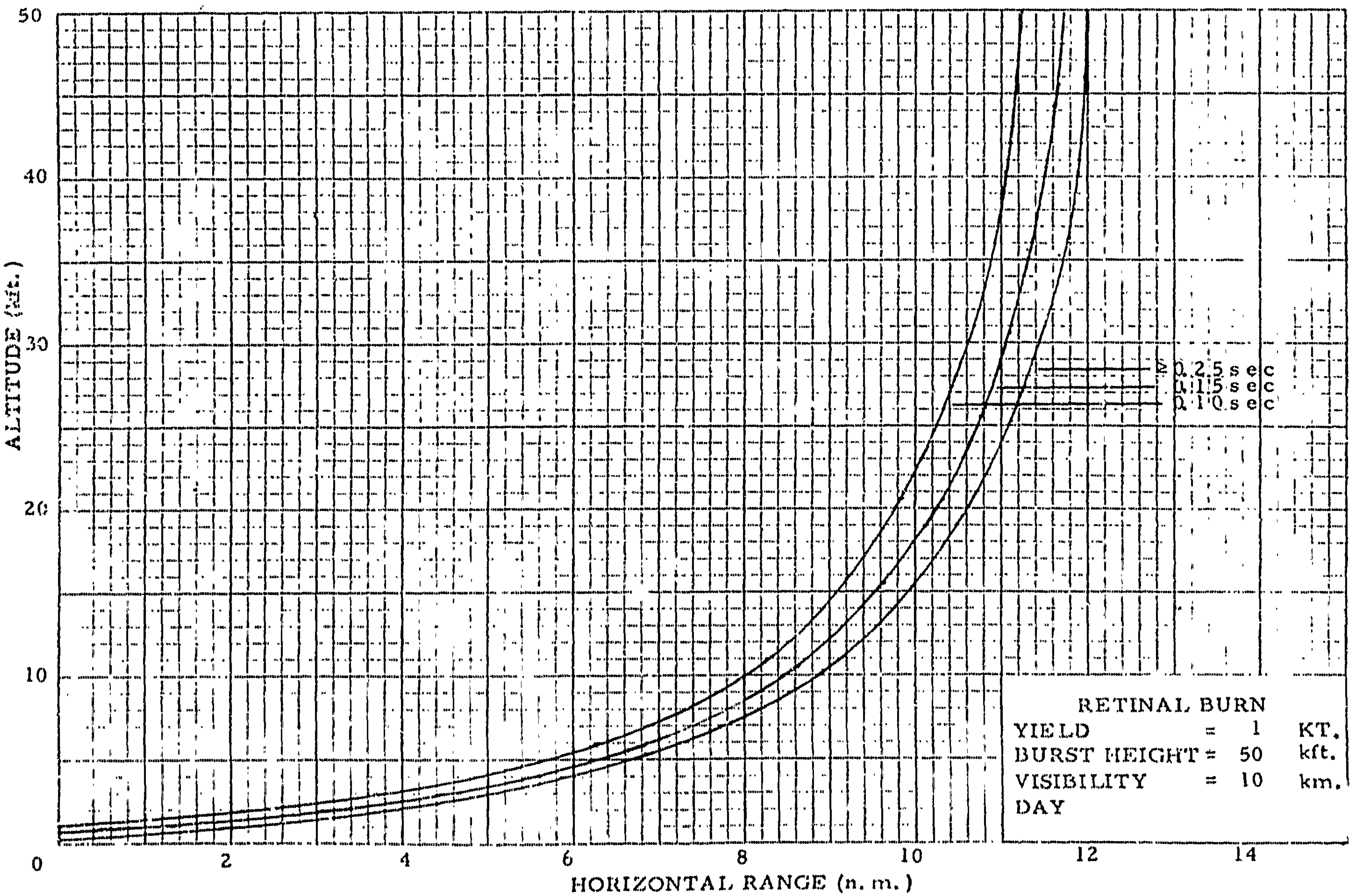
A 7

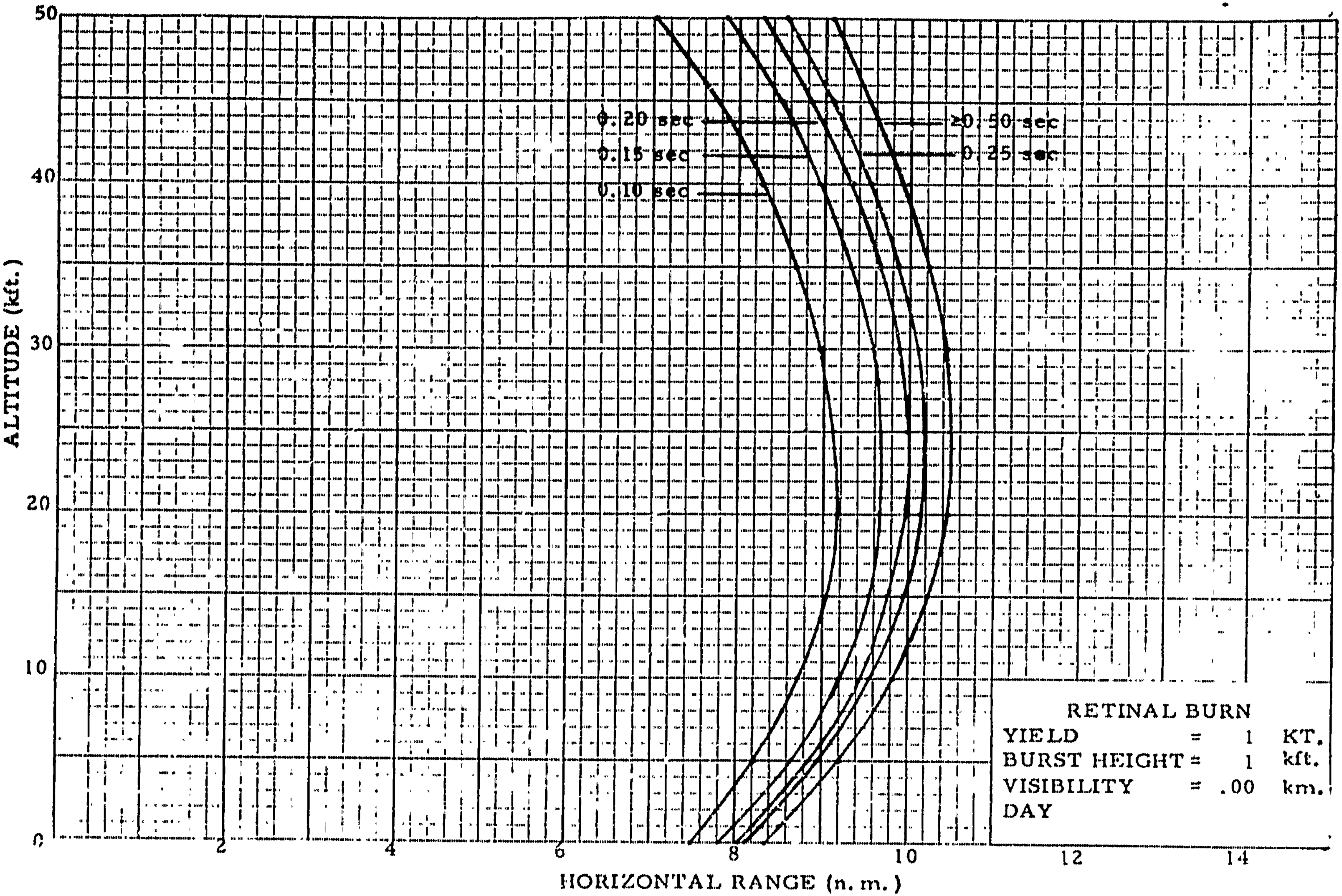


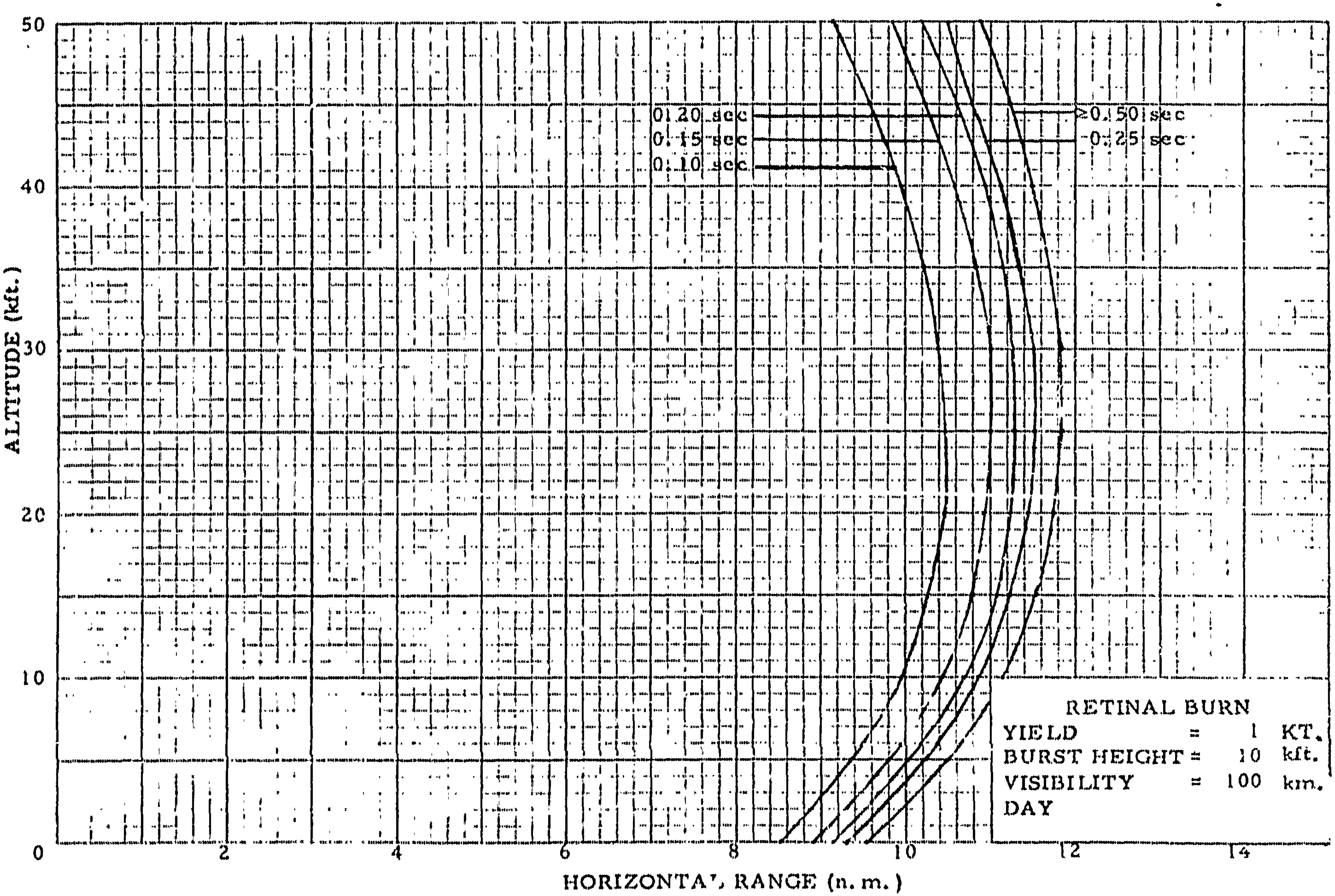
50
40
30
20
10
0
ALTITUDE (kft.)
1
2
3
4
5
6
7
HORIZONTAL RANGE (n. m.)
≥0.15 sec
0.10 sec
RETINAL BURN
YIELD = 0.1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY

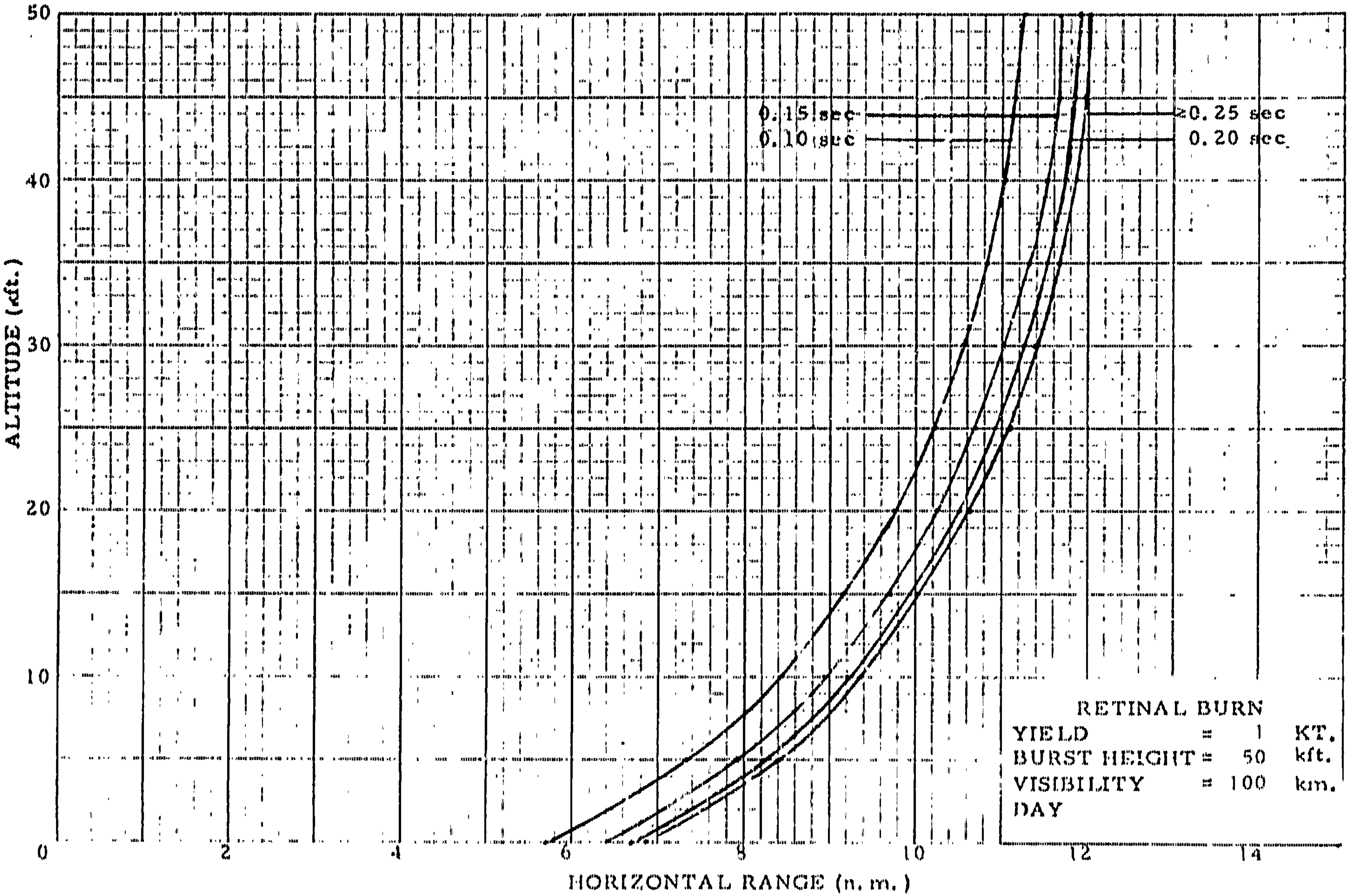

RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
DAY
0.15 sec
0.10 sec
≥0.50 sec
0.25 sec
0.20 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
1
2
3
4
5
6
7
10
20
30
40
50

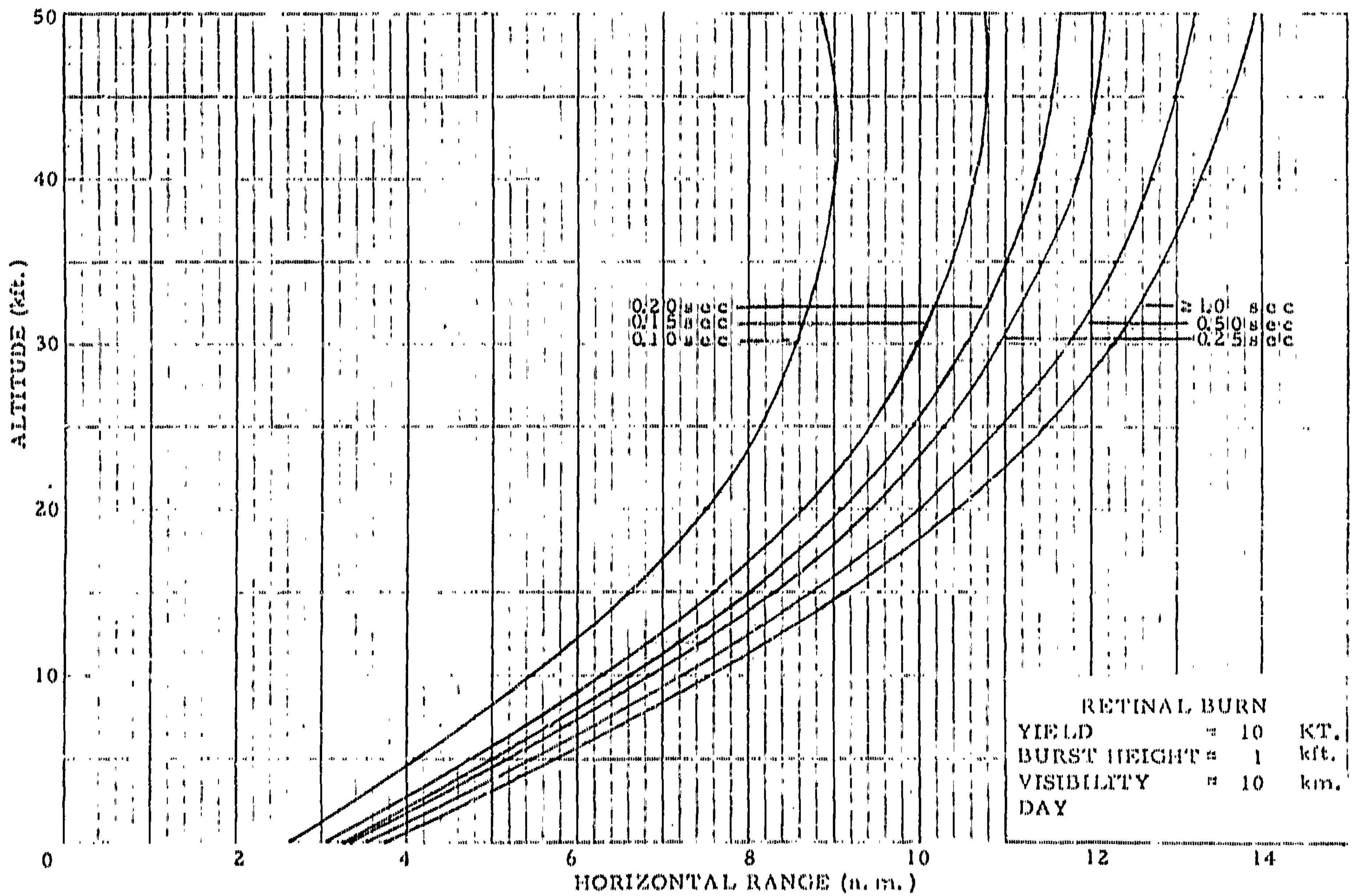

RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
DAY
≥0.50 sec
0.25 sec
0.15 sec
0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
2
4
6
8
10
12
14


ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
≥ 0.25 sec
0.15 sec
0.10 sec
RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
DAY

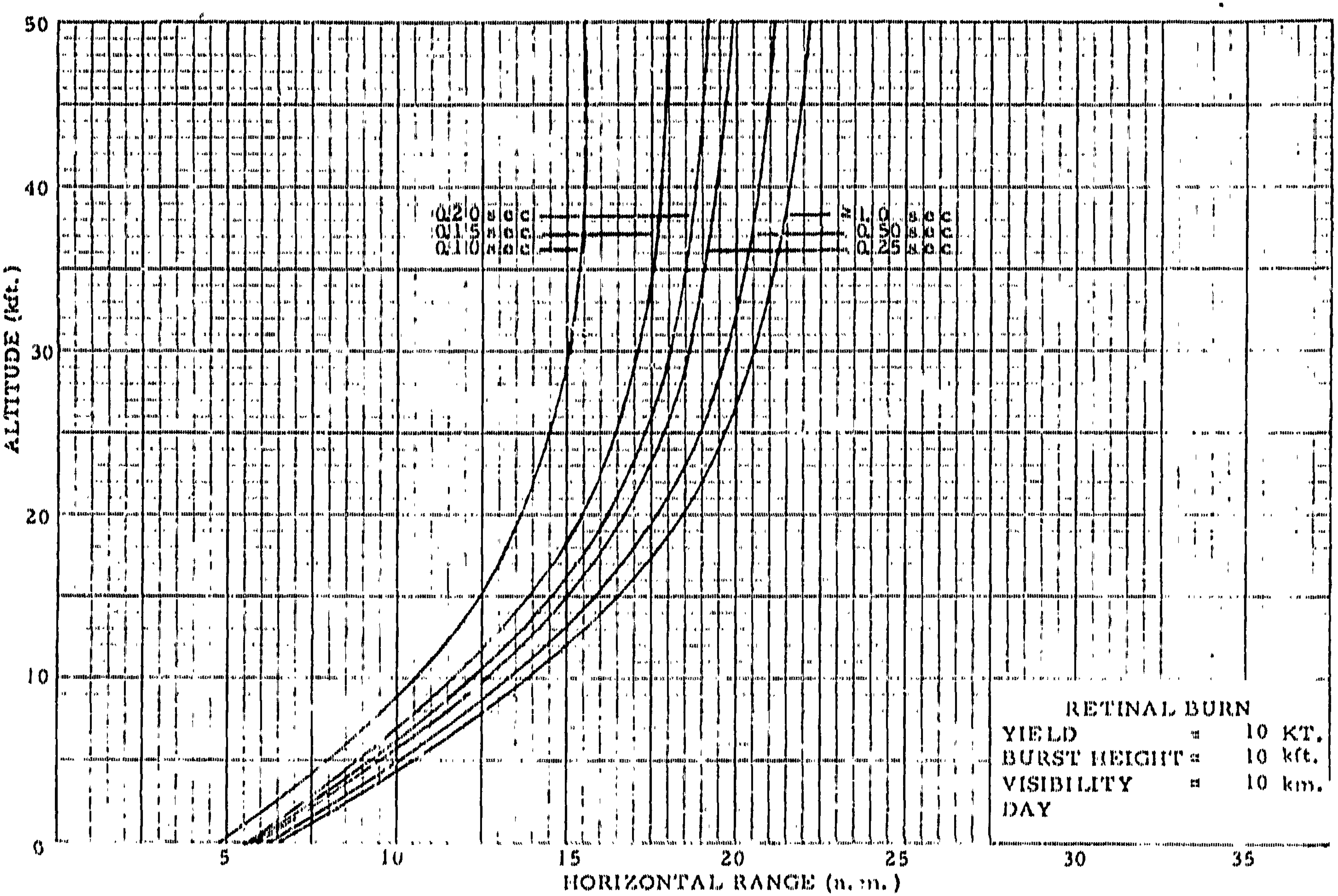

0.20 sec
0.15 sec
0.10 sec
≥0.50 sec
0.25 sec
RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = .00 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
2
4
6
8
10
12
14

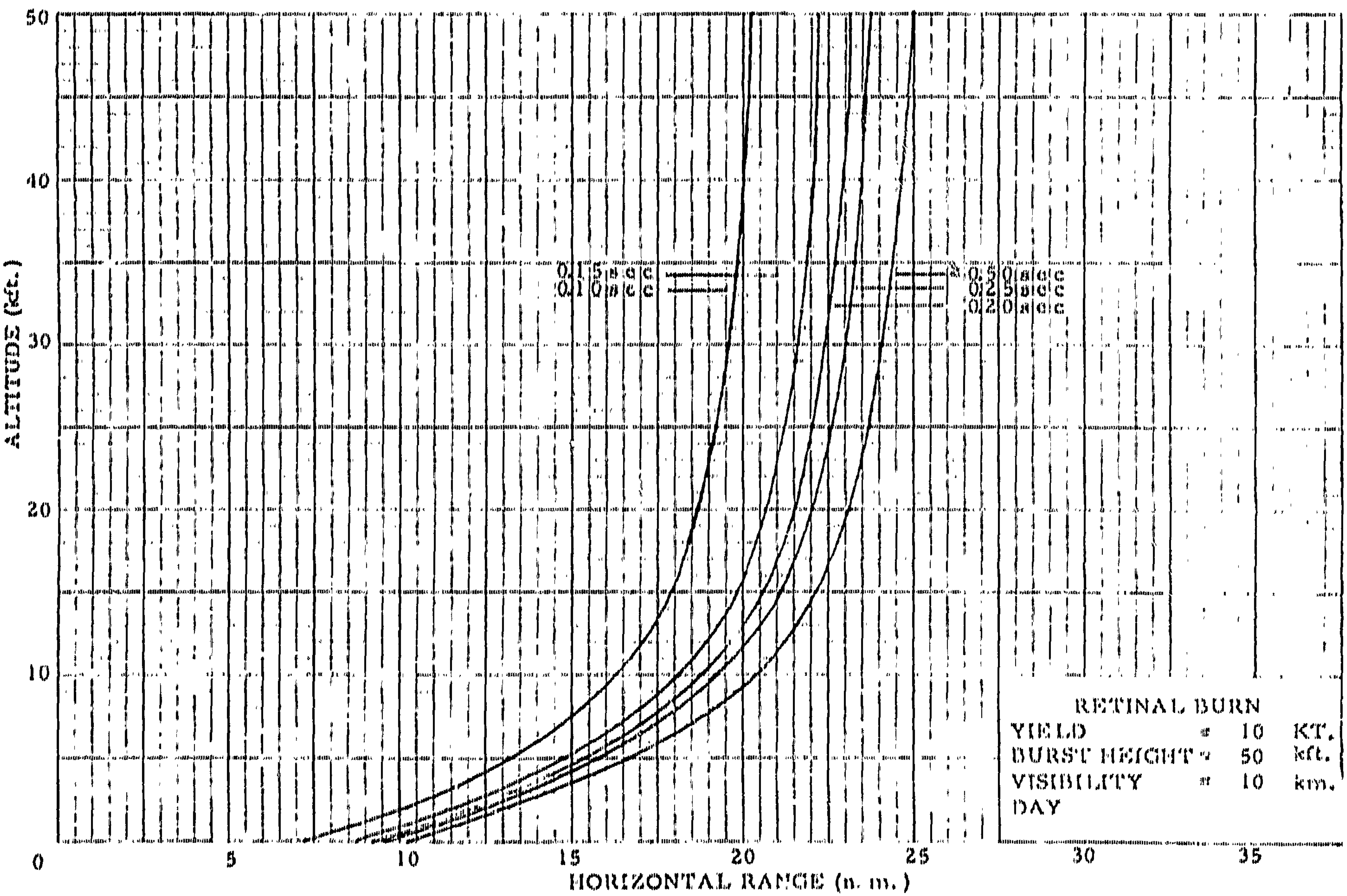

0.20 sec
0.15 sec
0.10 sec
≥0.50 sec
0.25 sec
RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
50
40
30
20
10
0
2
4
6
8
10
12
14

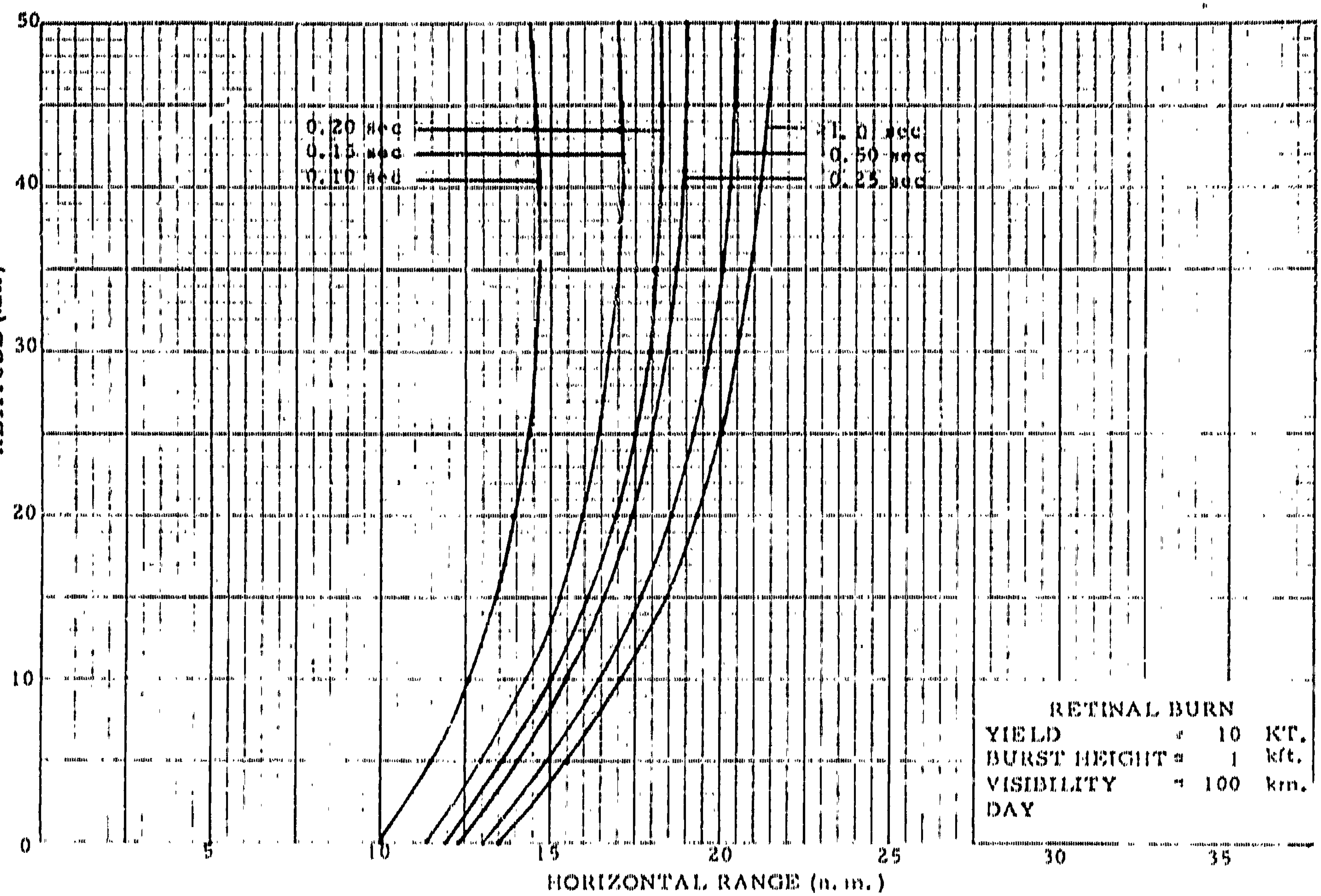

0.15 sec
0.10 sec
≥0.25 sec
0.20 sec
RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
2
4
6
8
10
12
14

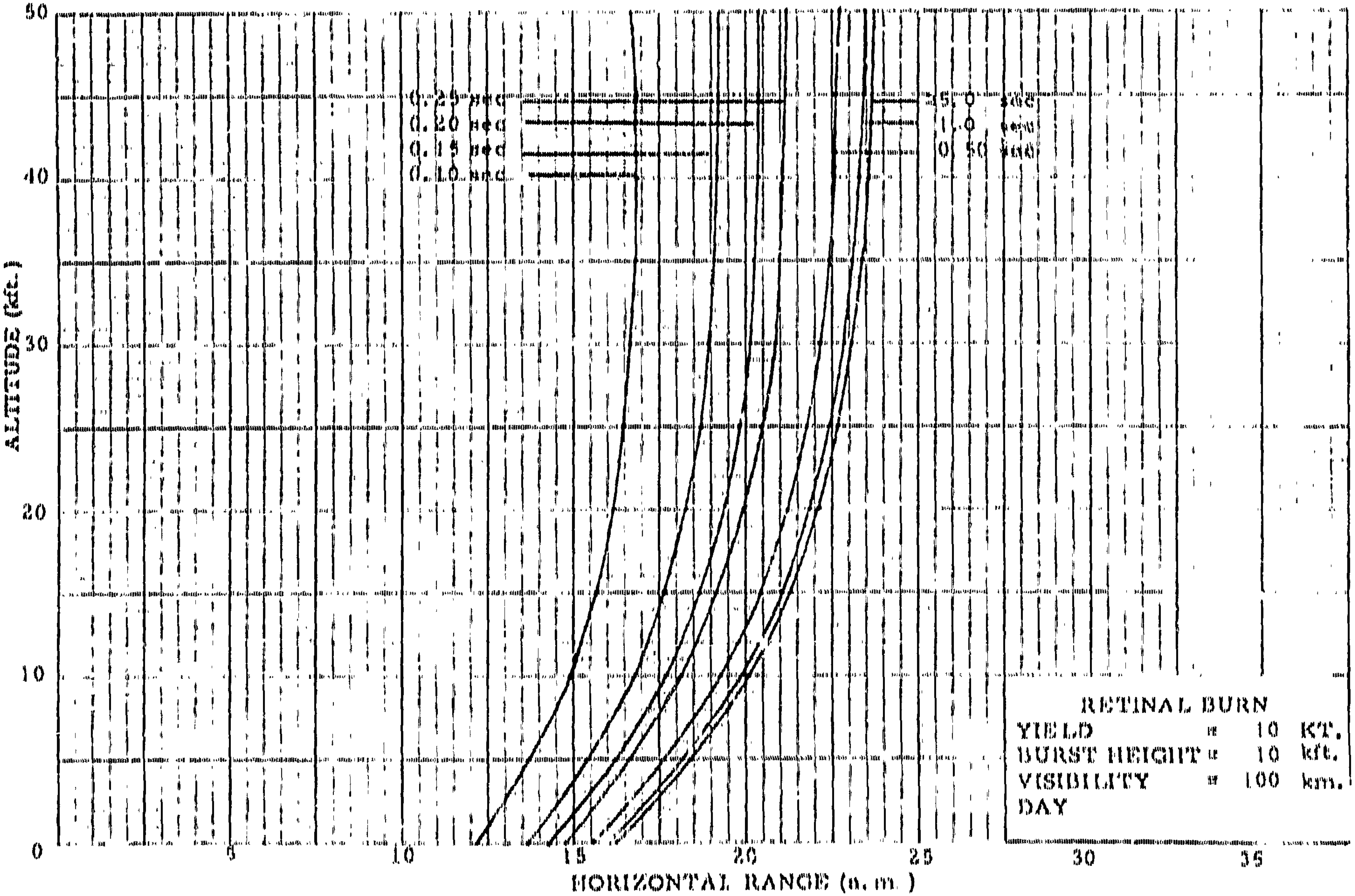


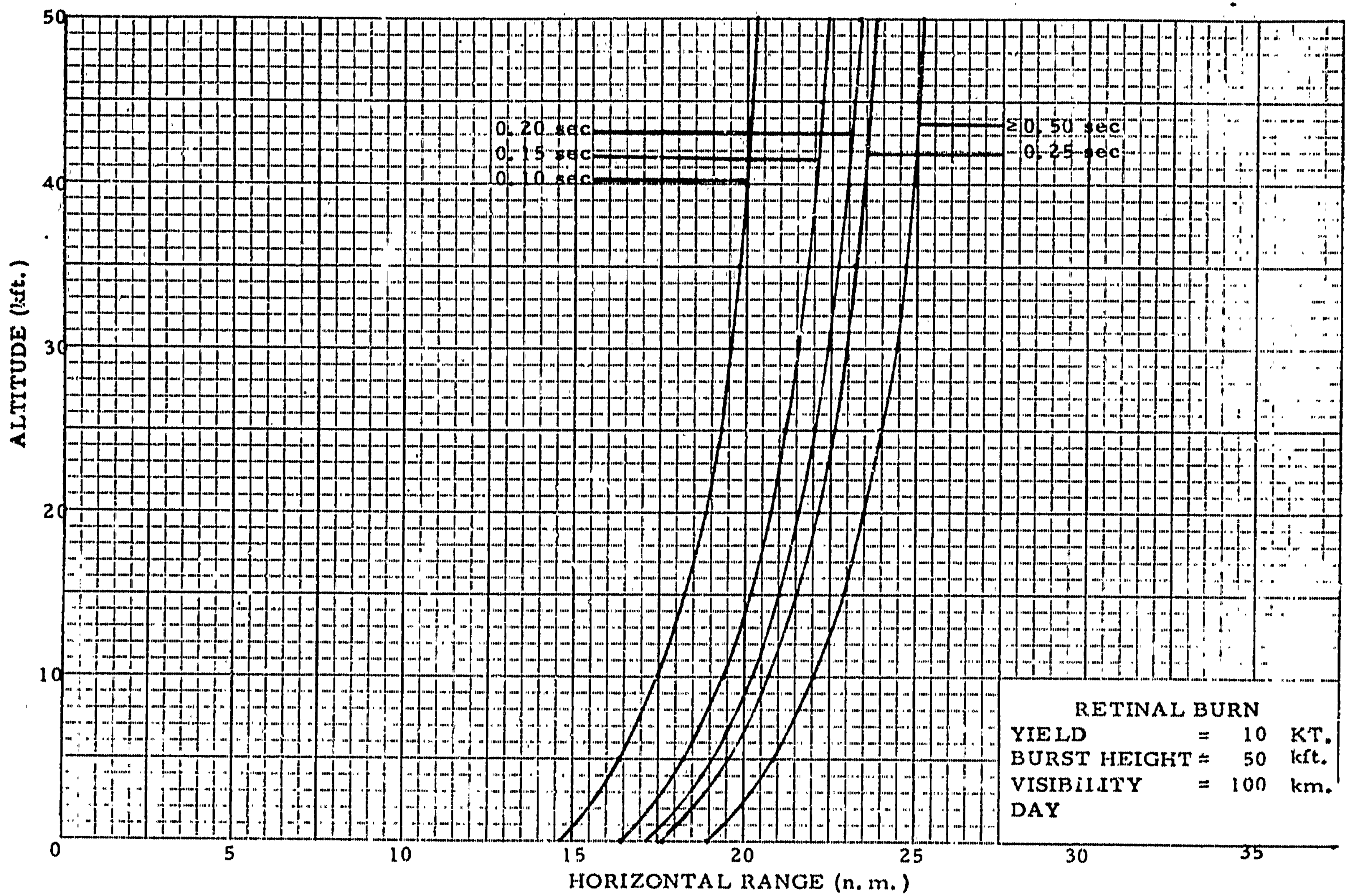
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
DAY
0.20 sec
0.15 sec
0.10 sec
1.0 sec
0.50 sec
0.25 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
2
4
6
8
10
12
14
10
20
30
40
50

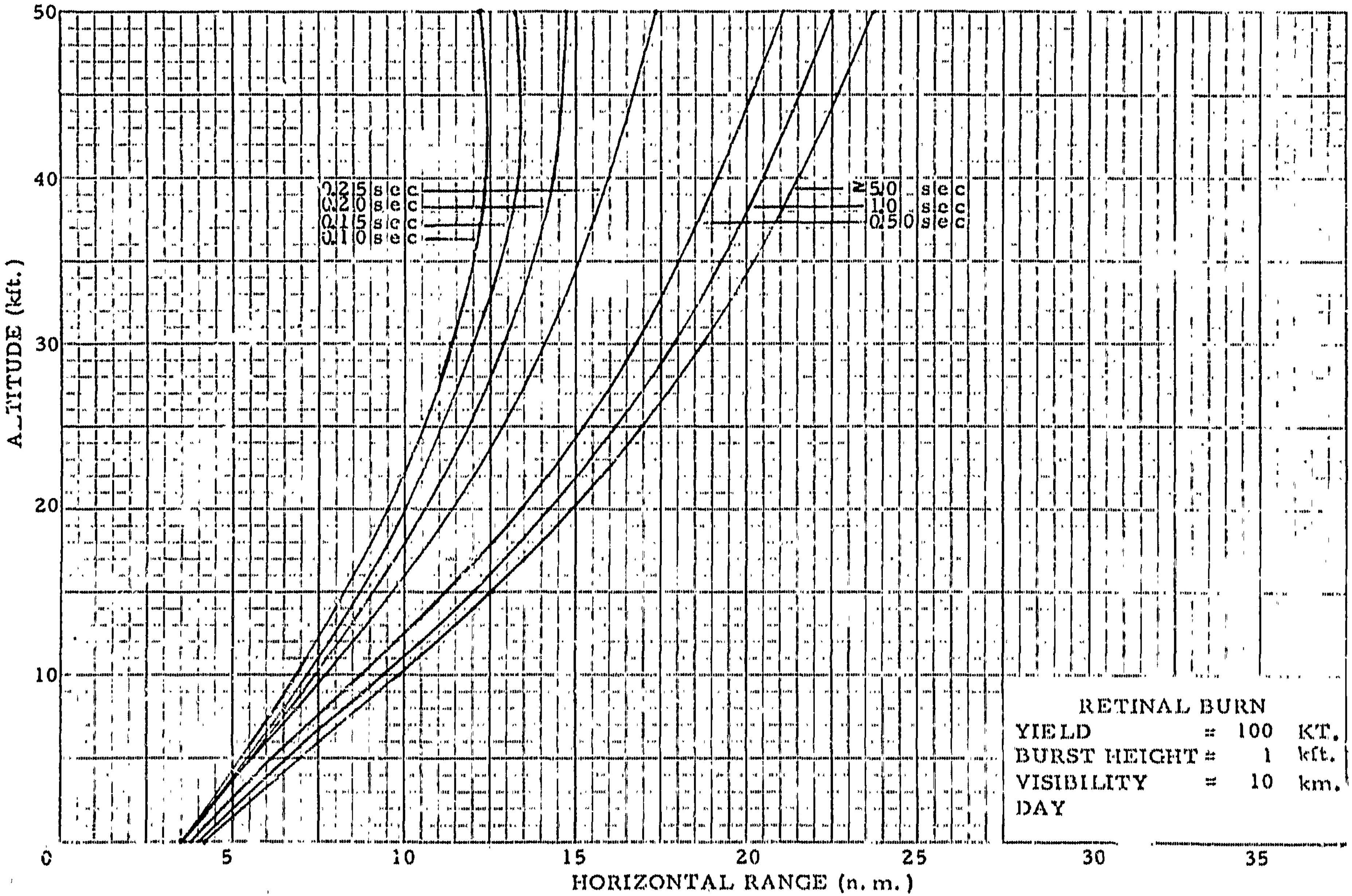

ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n. m.)
5
10
15
20
25
30
35
0.20 sec
0.15 sec
0.10 sec
1.0 sec
0.50 sec
0.25 sec
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
DAY


0.15 sec
0.10 sec
0.50 sec
0.25 sec
0.20 sec
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
5
10
15
20
25
30
35
10
20
30
40
50

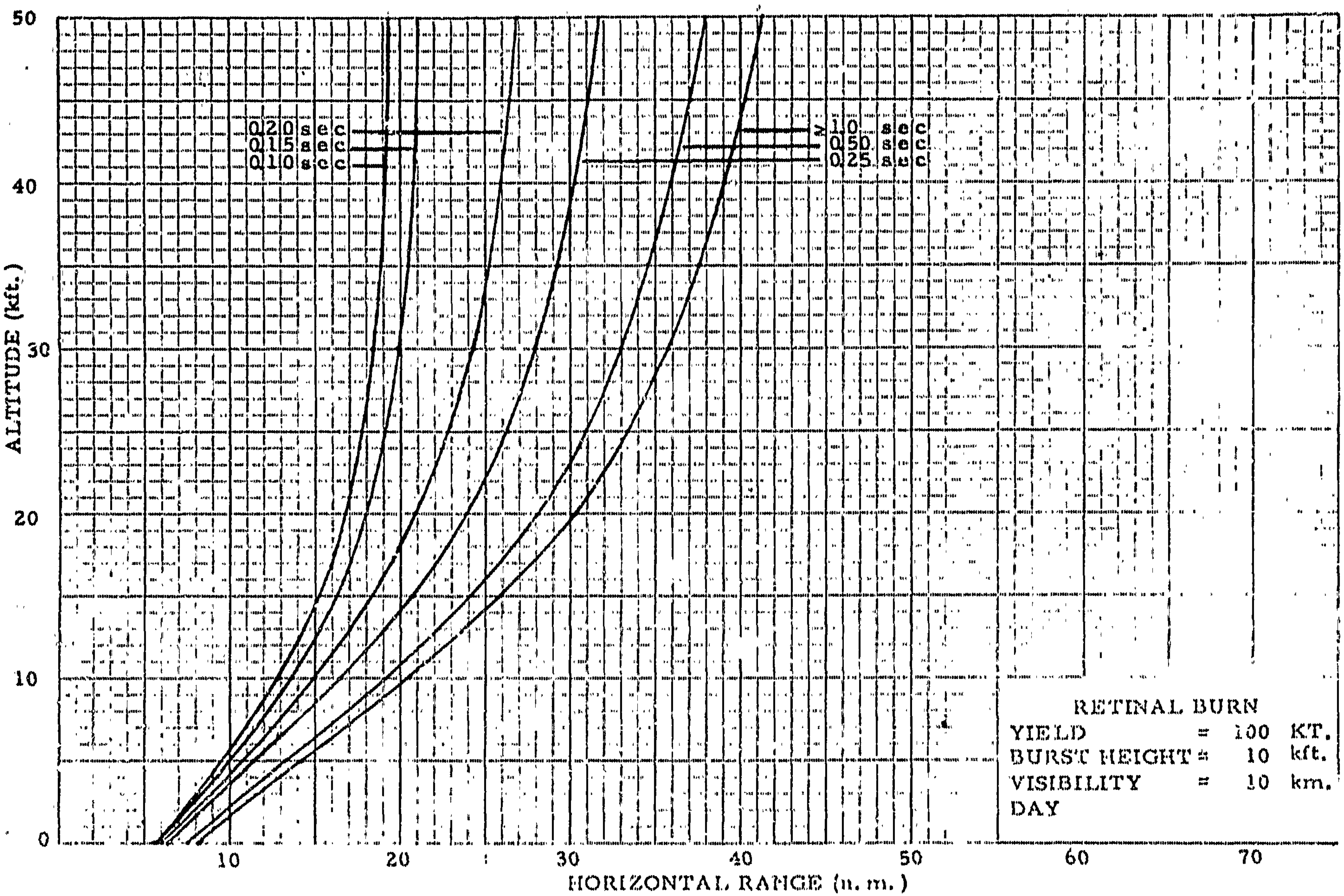

0.20 sec
0.15 sec
0.10 sec
1.0 sec
0.50 sec
0.25 sec
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
5
15
25
35

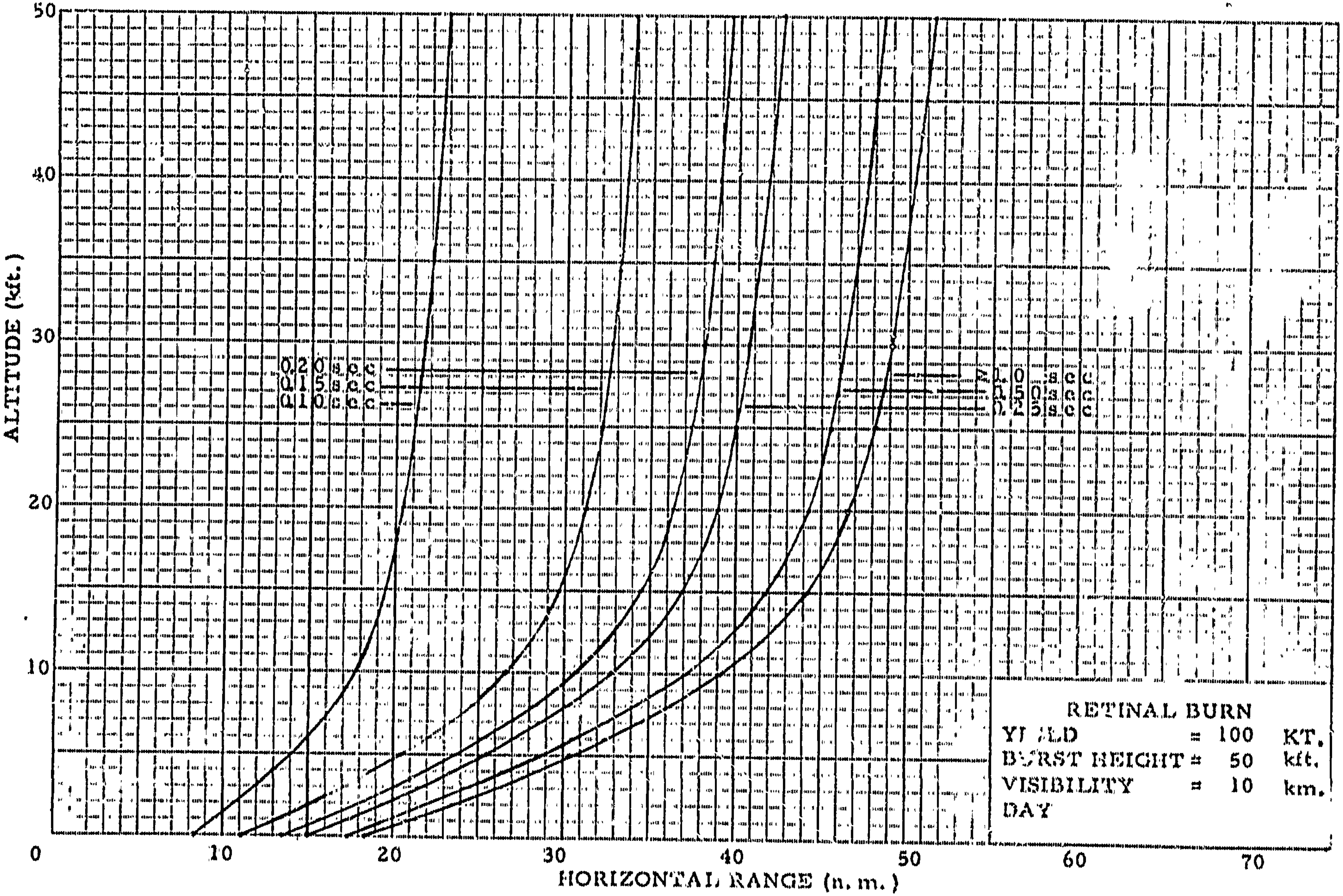

0.25 sec
0.20 sec
0.15 sec
0.10 sec
5.0 sec
1.0 sec
0.50 sec
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
5
10
15
20
25
30
35
40
50

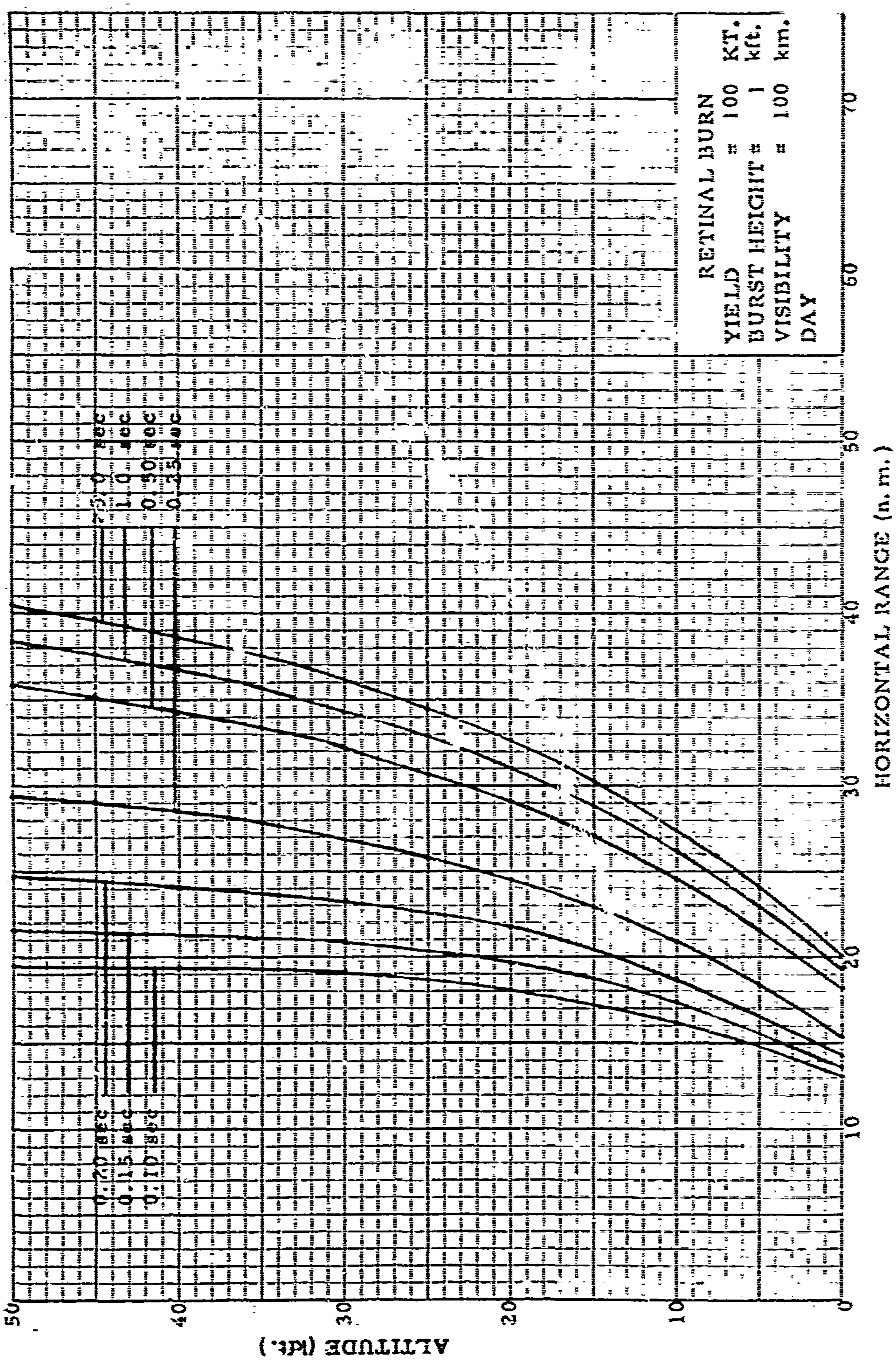

0.20 sec
0.15 sec
0.10 sec
≥0.50 sec
0.25 sec
50
40
30
20
10
0
5
10
15
20
25
30
35
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY



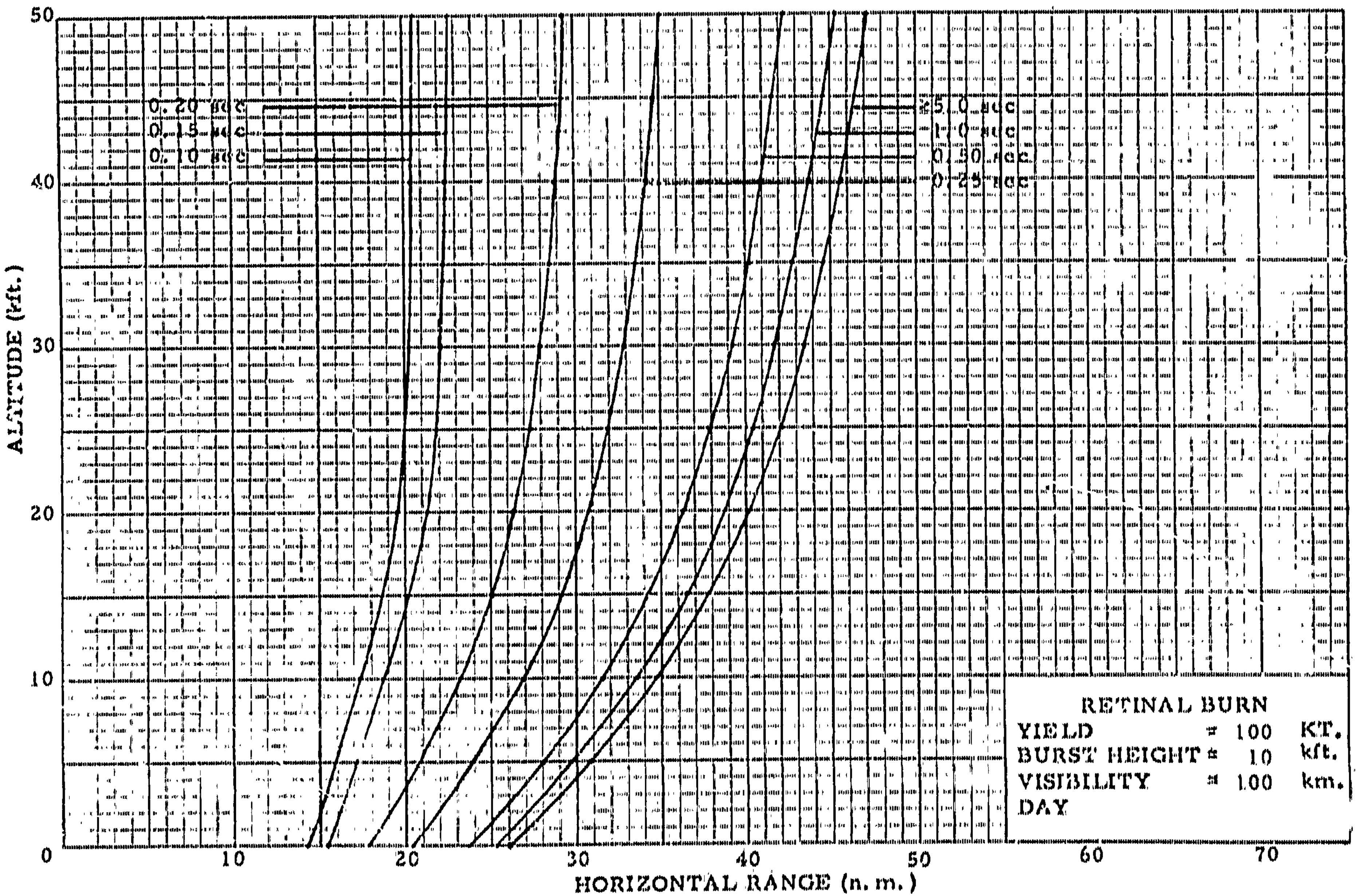
0.25 sec
0.20 sec
0.15 sec
0.10 sec
≥5.0 sec
1.0 sec
0.50 sec
RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
5
10
15
20
25
30
35
40
50

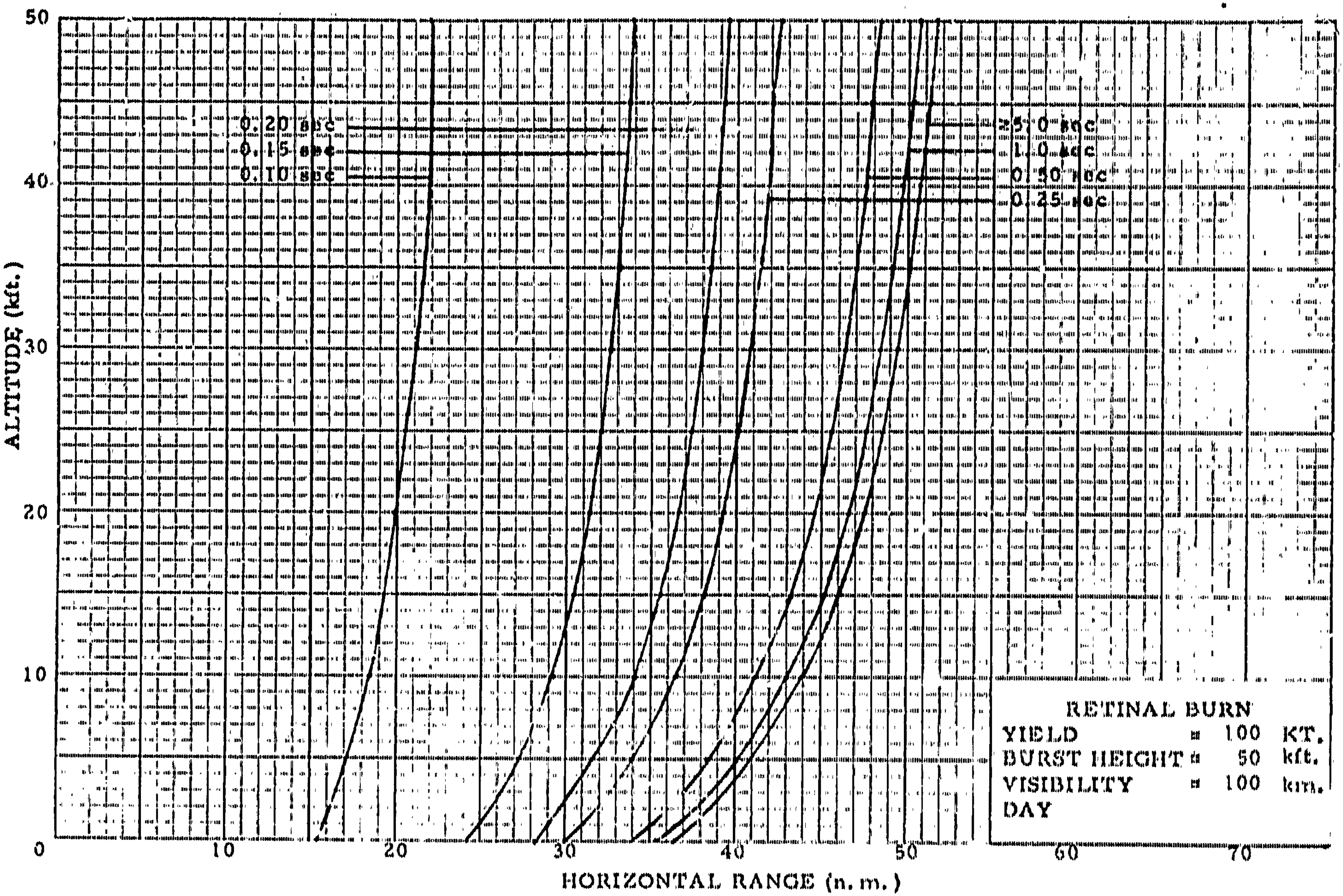

0.20 sec
0.15 sec
0.10 sec
≥ 1.0 sec
0.50 sec
0.25 sec
RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70

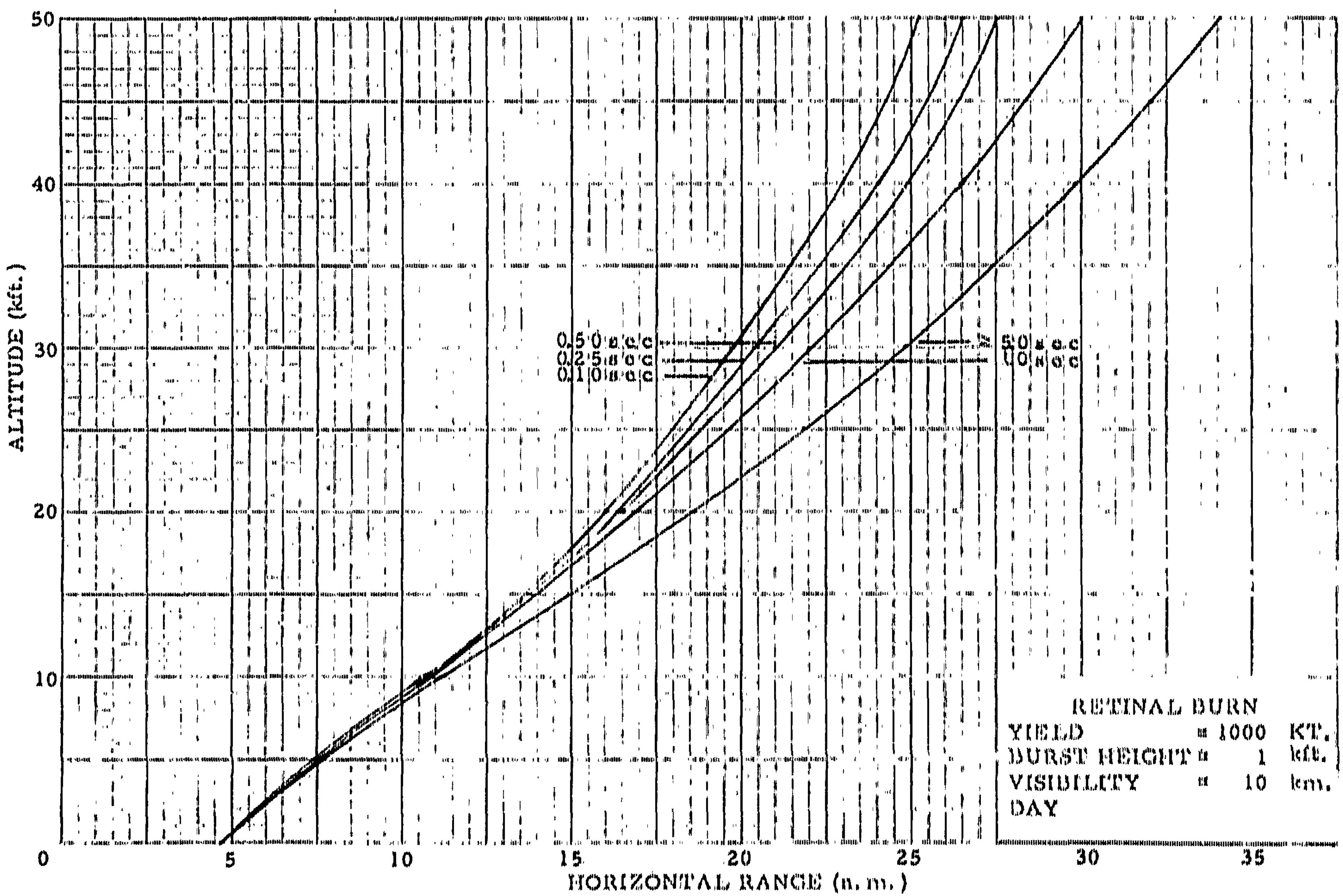

ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70
0.20 sec
0.15 sec
0.10 sec
1.0 sec
0.50 sec
0.25 sec
RETINAL BURN
YI LD = 100 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
DAY

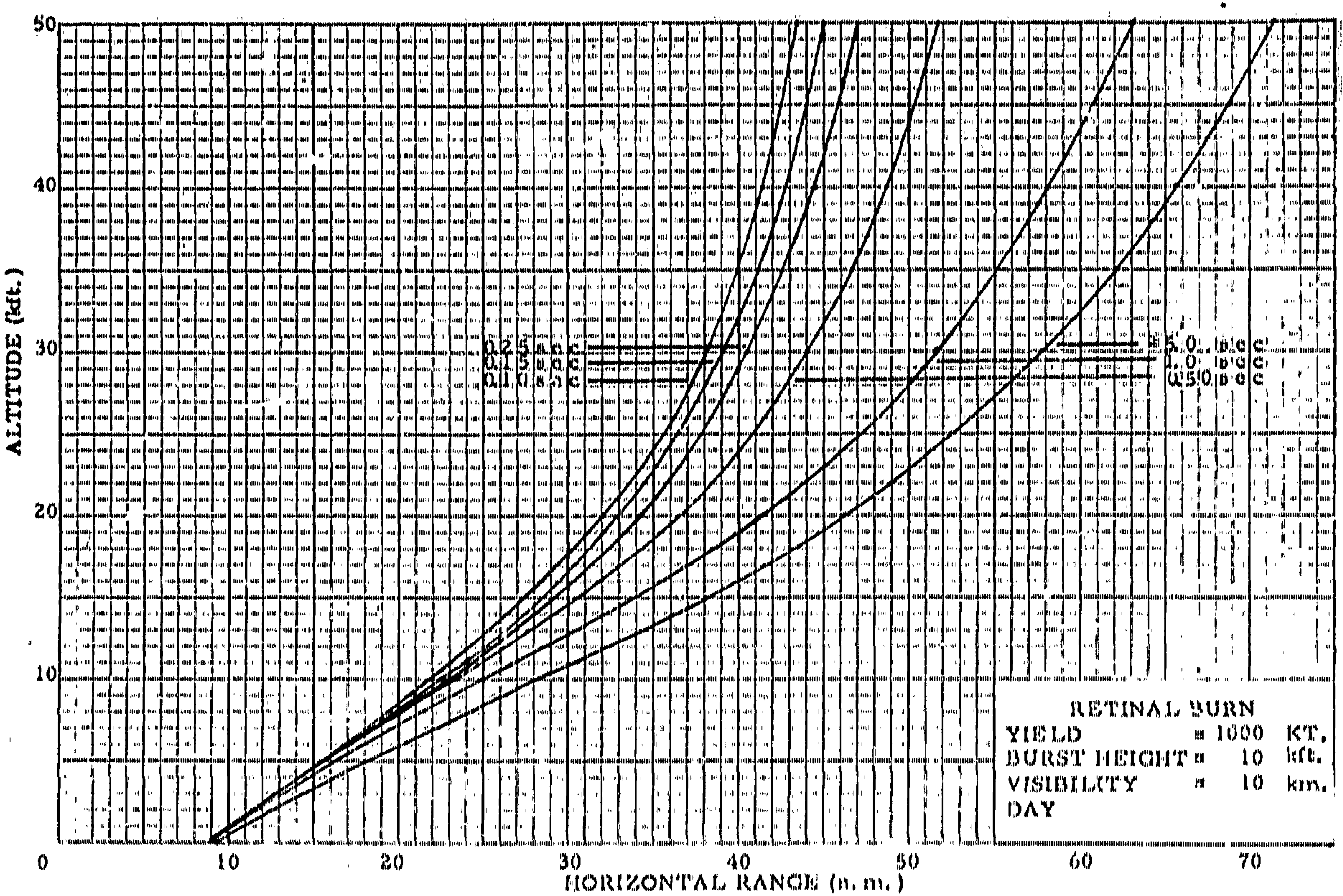


RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY
1.0 sec
0.50 sec
0.25 sec
0.20 sec
0.15 sec
0.10 sec
HORIZONTAL RANGE (n. m.)
ALTITUDE (kft.)

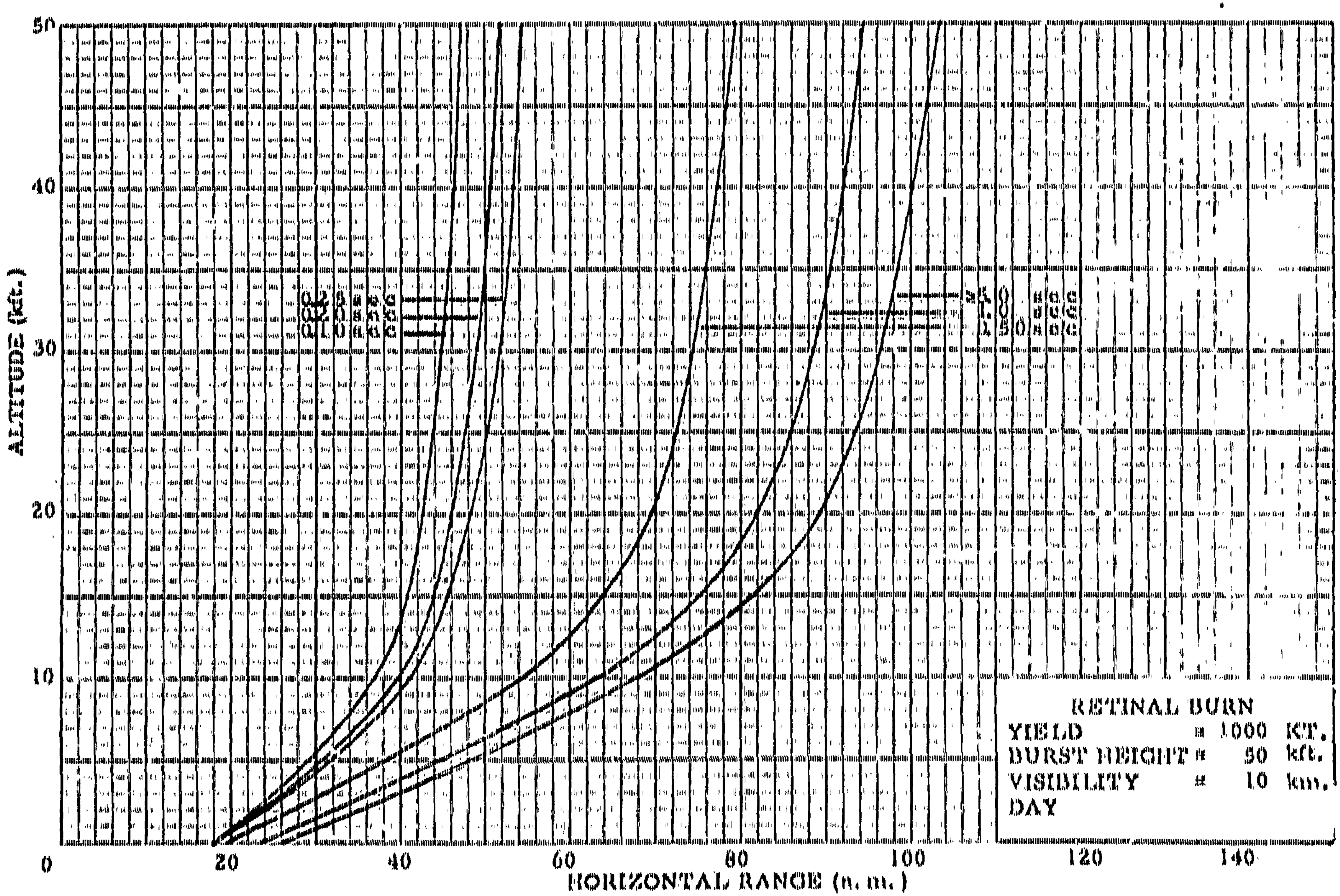

RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY
0.20 sec
0.15 sec
0.10 sec
5.0 sec
1.0 sec
0.50 sec
0.25 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70

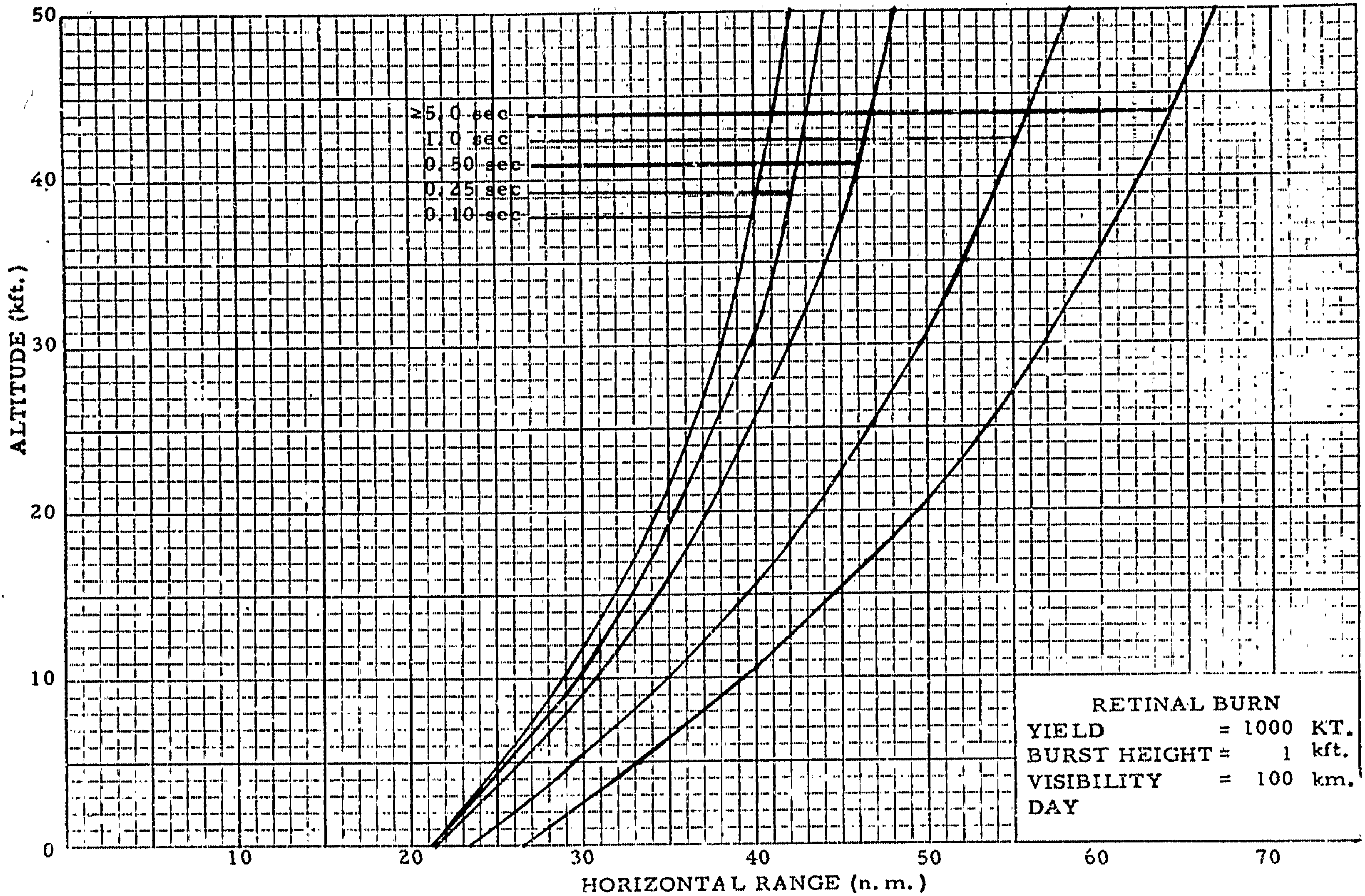

0.20 sec
0.15 sec
0.10 sec
25.0 sec
1.0 sec
0.50 sec
0.25 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70
RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY

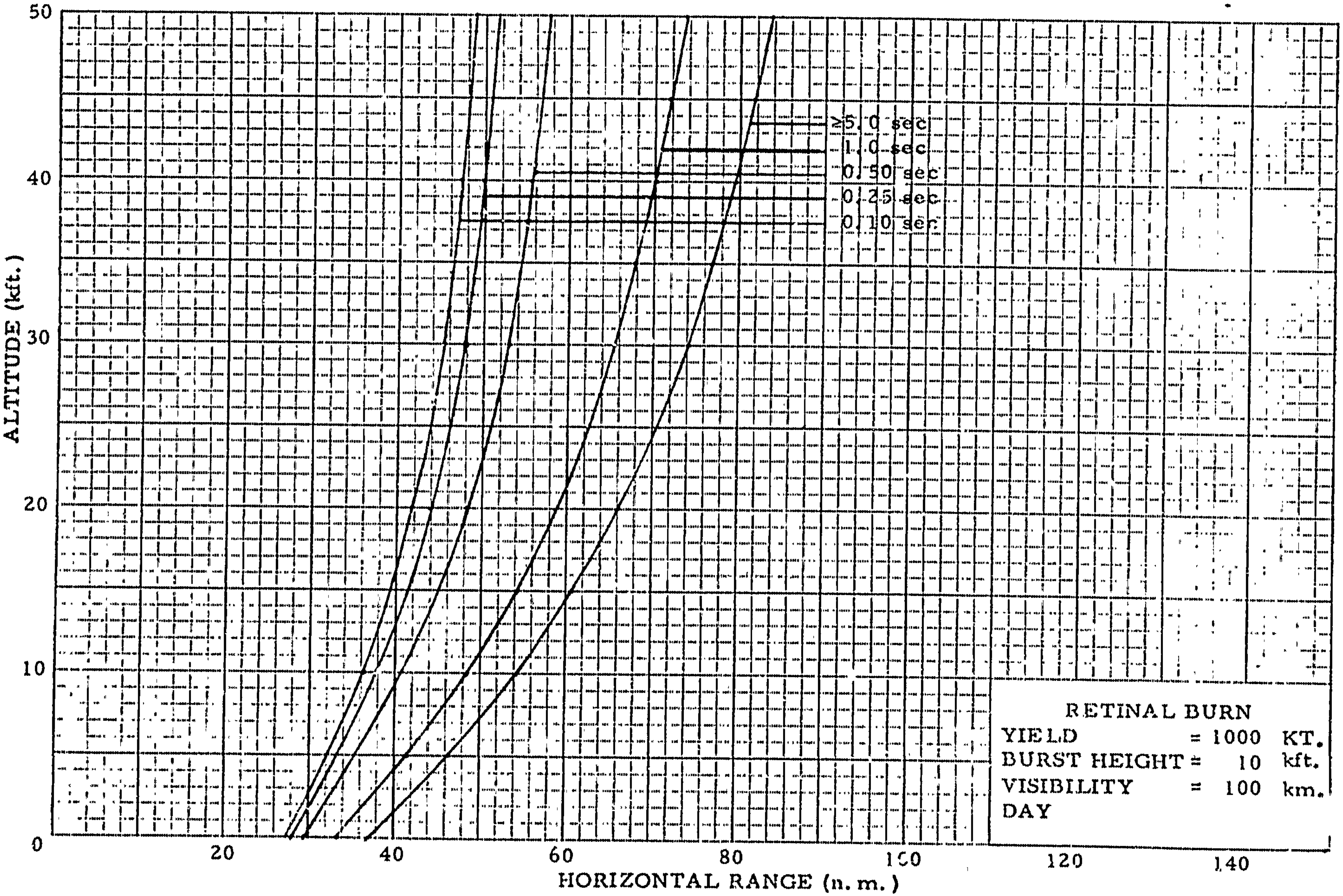

ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
5
10
15
20
25
30
35
10
20
30
40
50
0.50 sec
0.25 sec
0.10 sec
5.0 sec
1.0 sec
RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
DAY

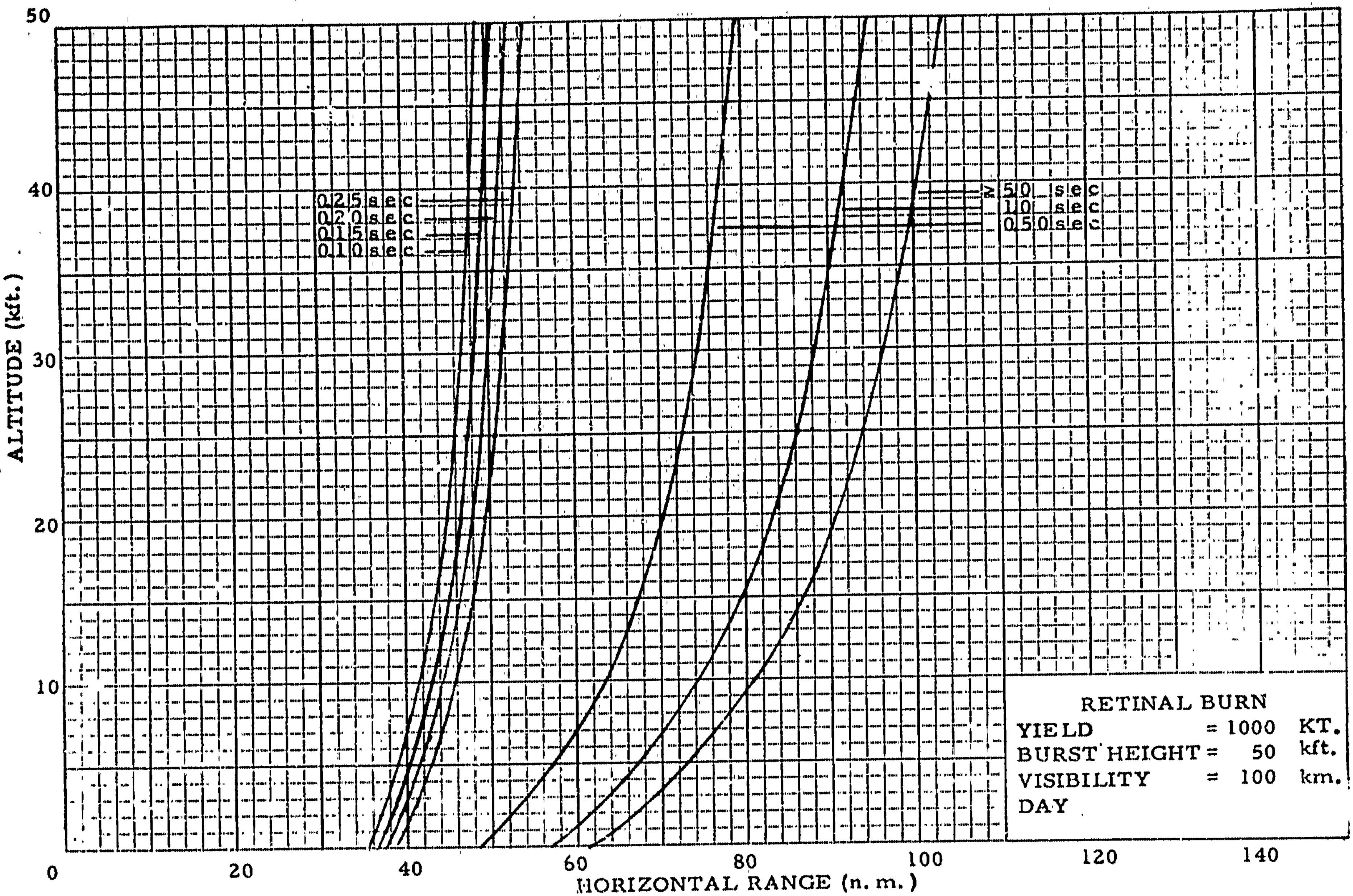


ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0.25 sec
0.15 sec
0.10 sec
5.0 sec
1.0 sec
0.50 sec
RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
DAY
0
10
20
30
40
50
60
70

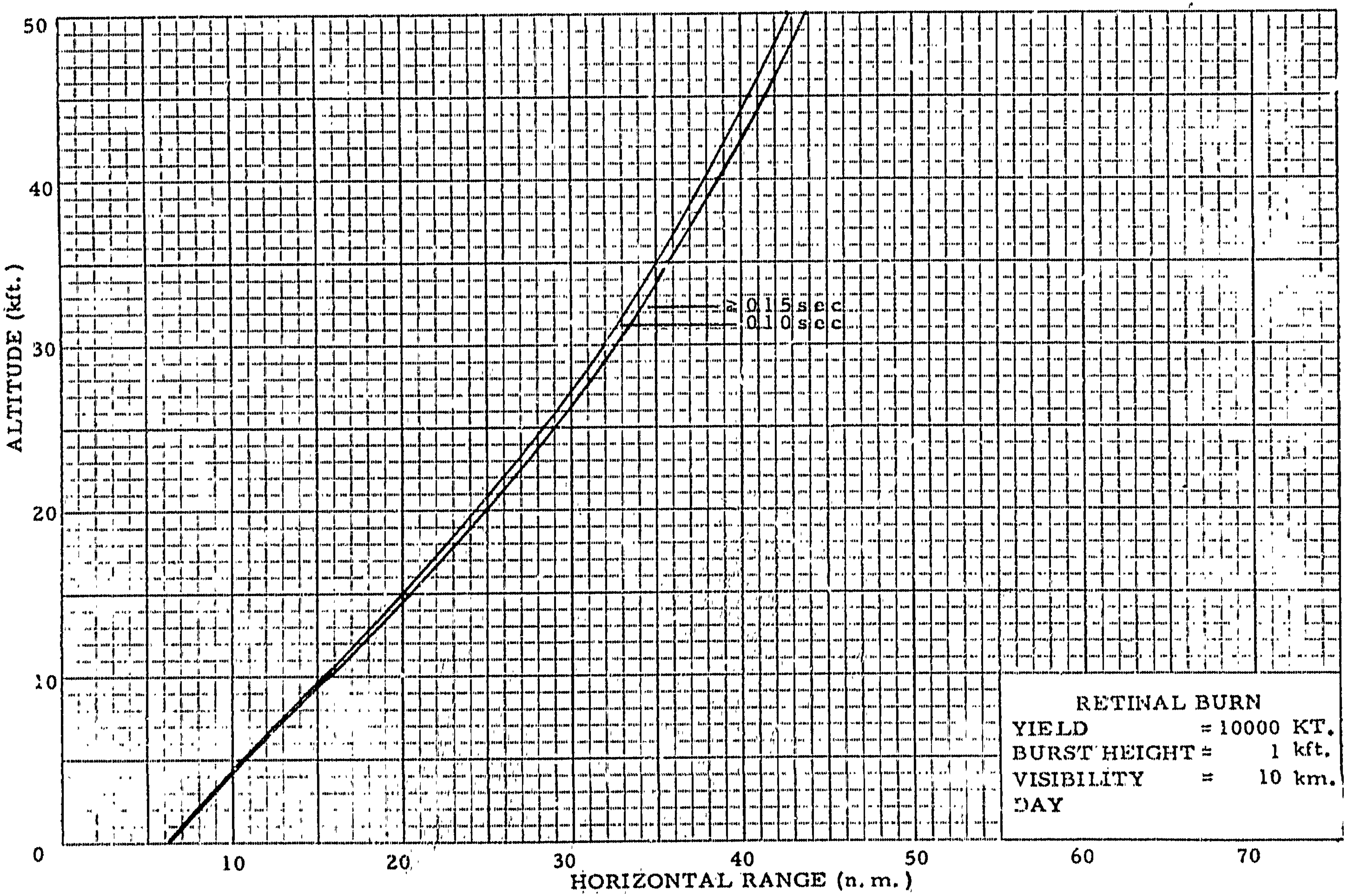

0.25 sec
0.20 sec
0.10 sec
5.0 sec
1.0 sec
0.50 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. mi.)
RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
DAY


≥5.0 sec
1.0 sec
0.50 sec
0.25 sec
0.10 sec
RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70

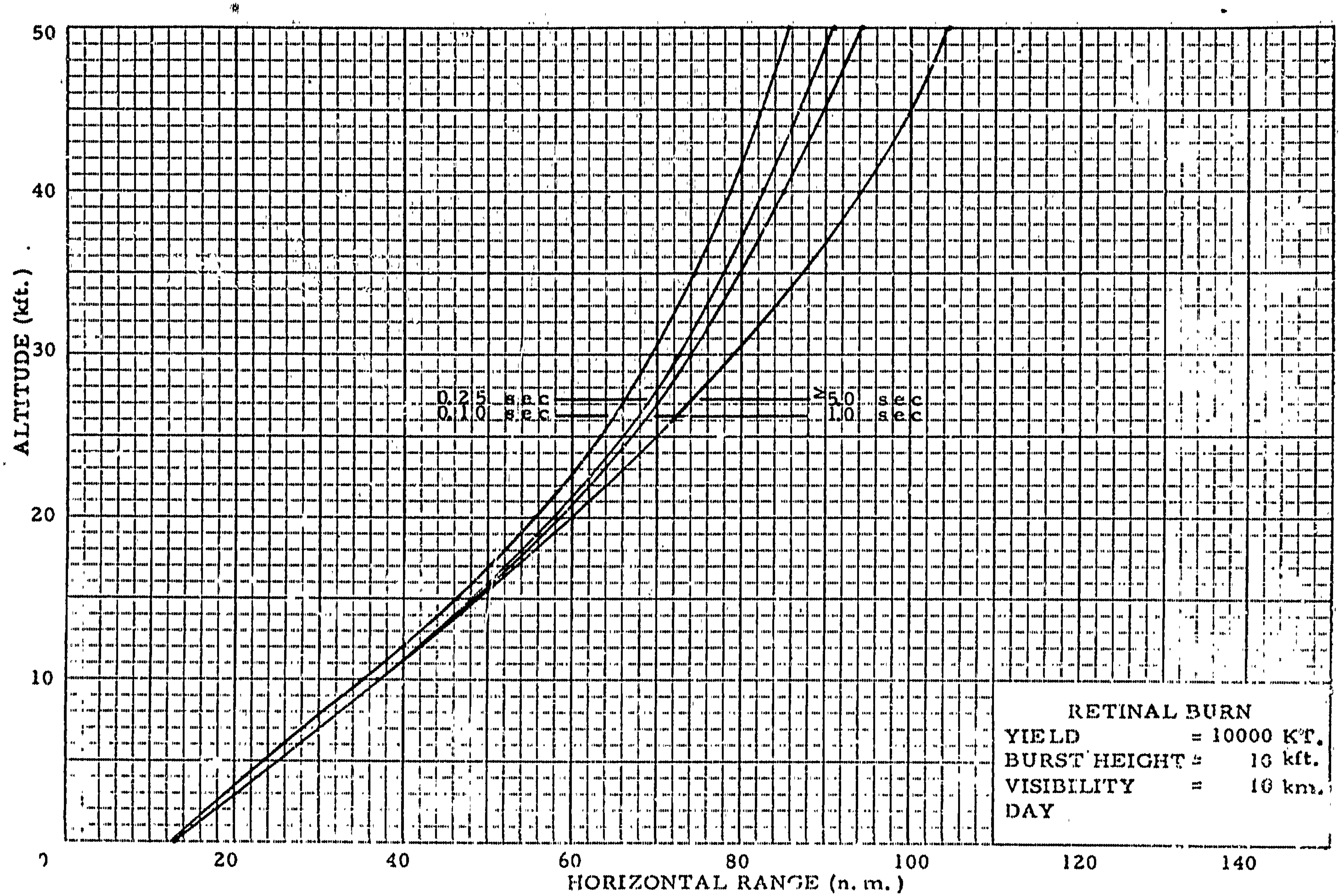

50
40
30
20
10
0
ALTITUDE (kft.)
20
40
60
80
100
120
140
HORIZONTAL RANGE (n. m.)
≥5.0 sec
1.0 sec
0.50 sec
0.25 sec
0.10 sec
RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY

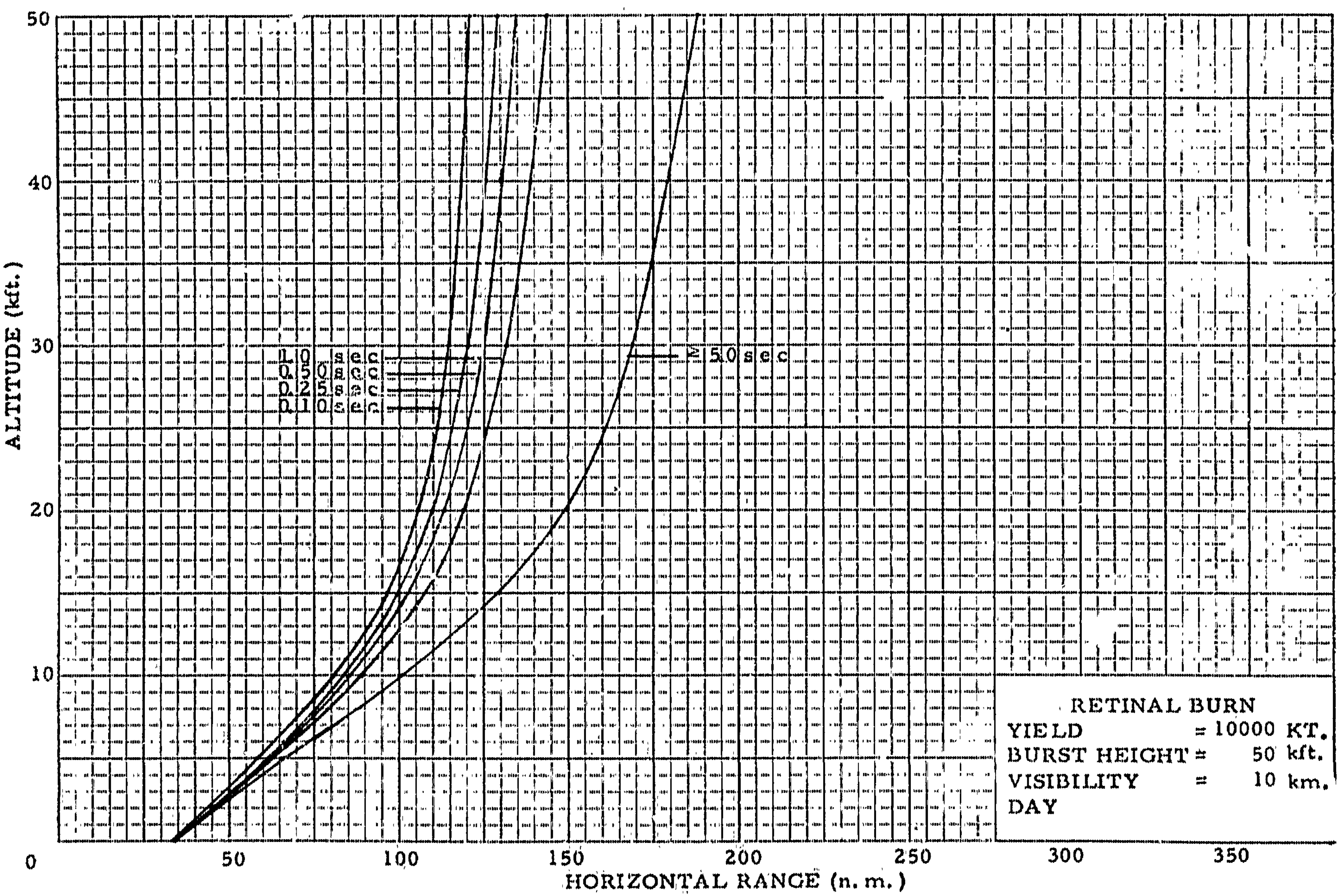


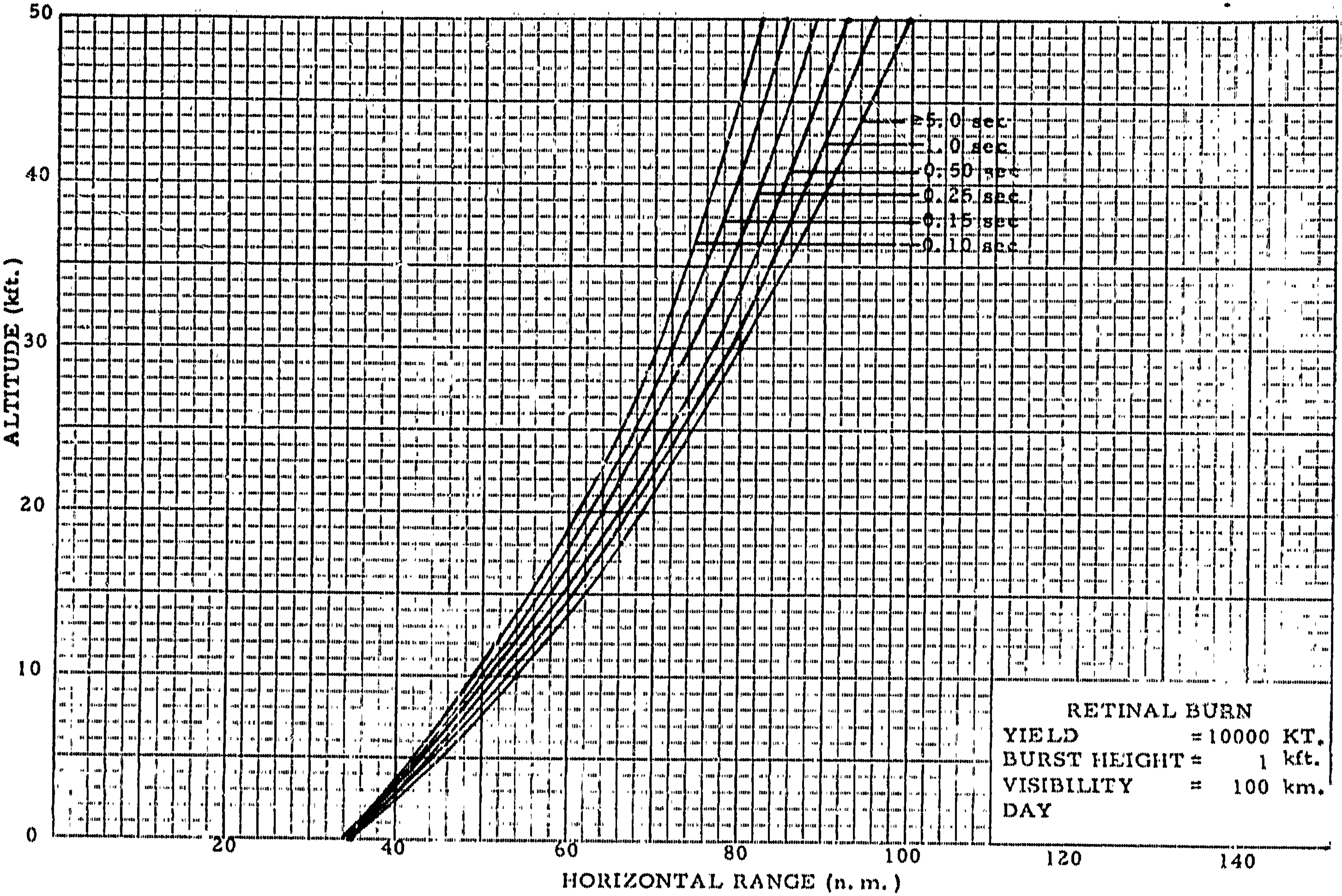
RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY
0.25 sec
0.20 sec
0.15 sec
0.10 sec
≥ 5.0 sec
1.0 sec
0.50 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
0
20
40
60
80
100
120
140



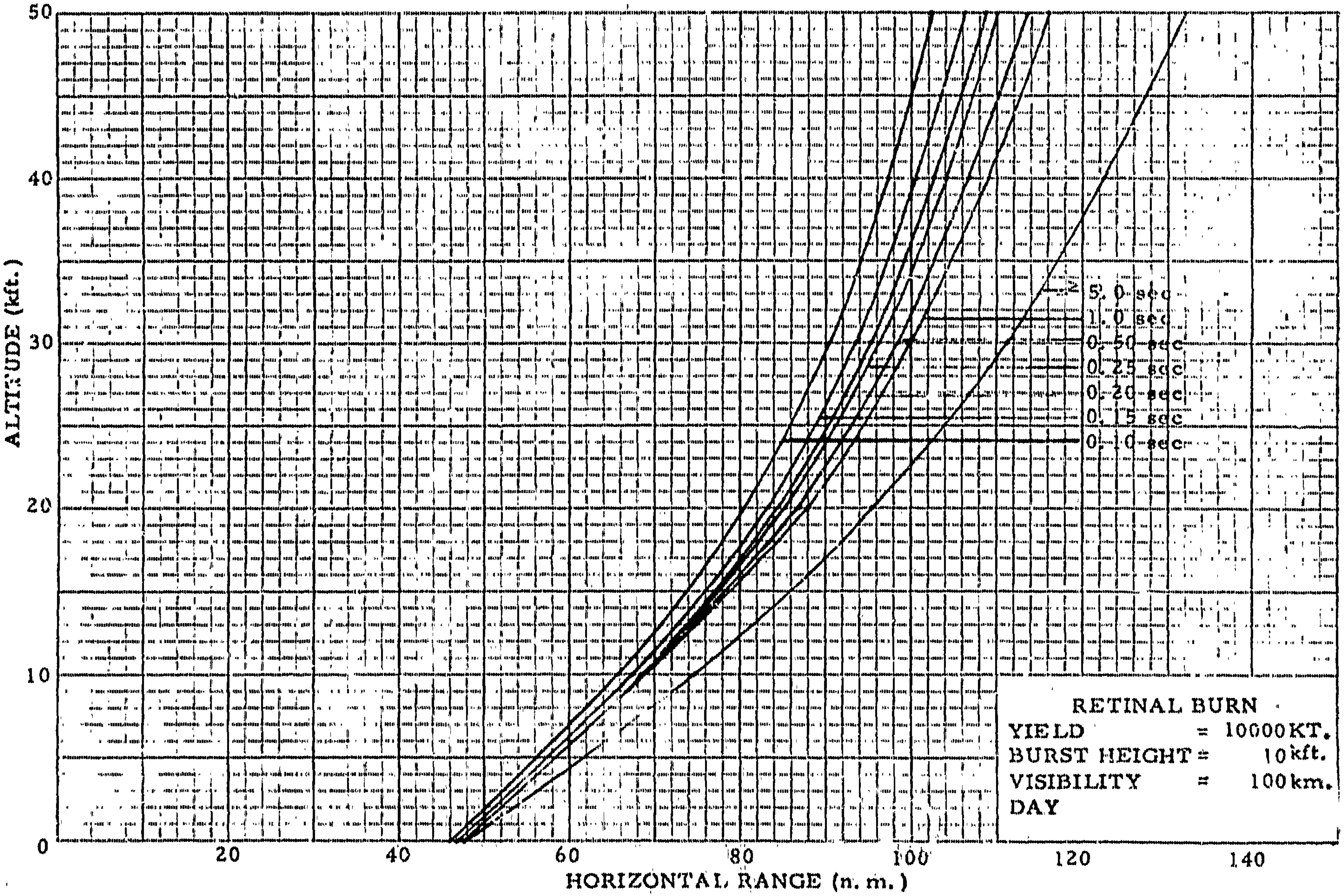
RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
DAY
≈ 0.15 sec
0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70


ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0.25 sec
0.10 sec
≥5.0 sec
1.0 sec
RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
DAY

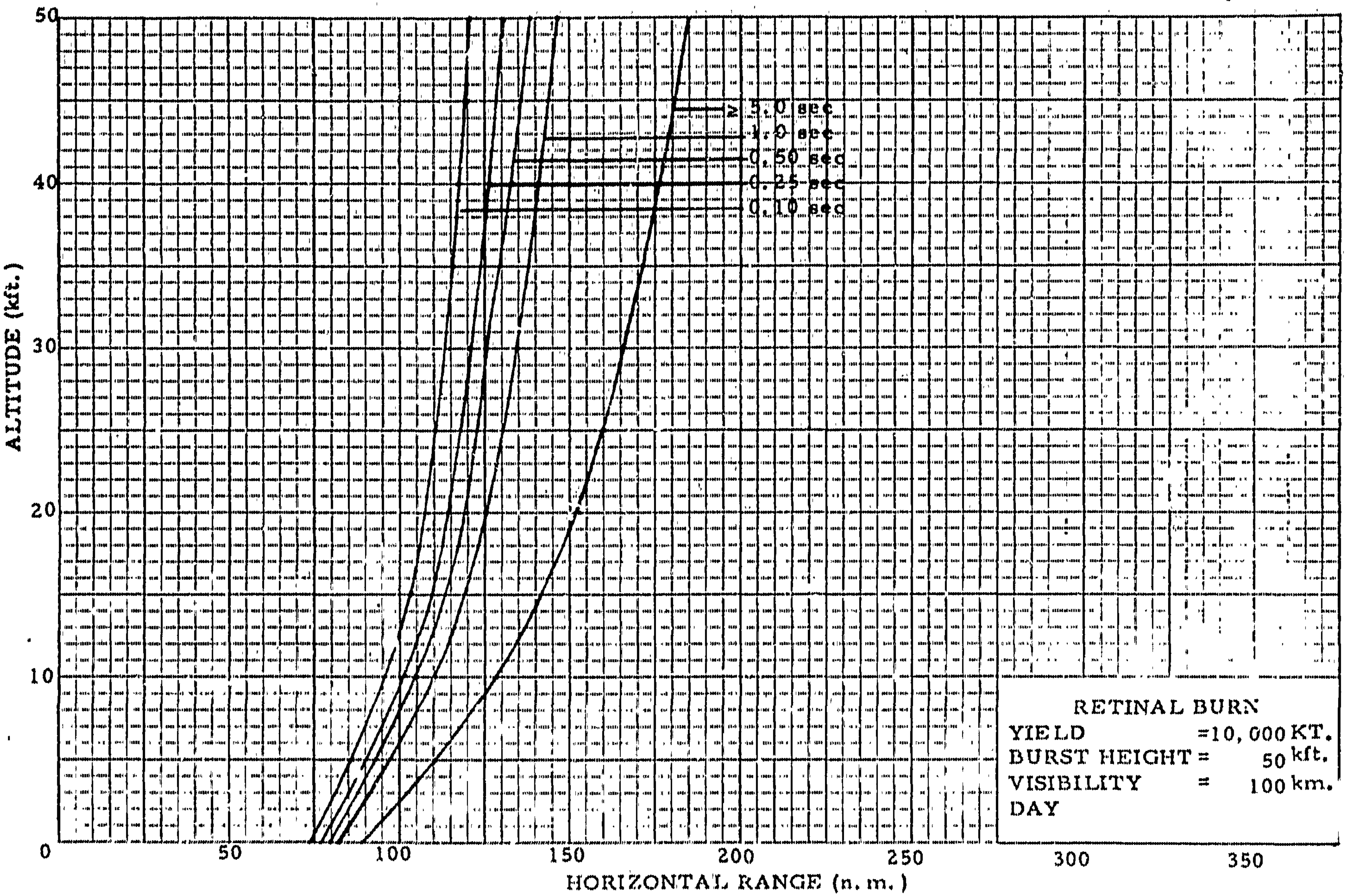

ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
50
100
150
200
250
300
350
1.0 sec
0.50 sec
0.25 sec
0.10 sec
≥ 5.0 sec
RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
DAY

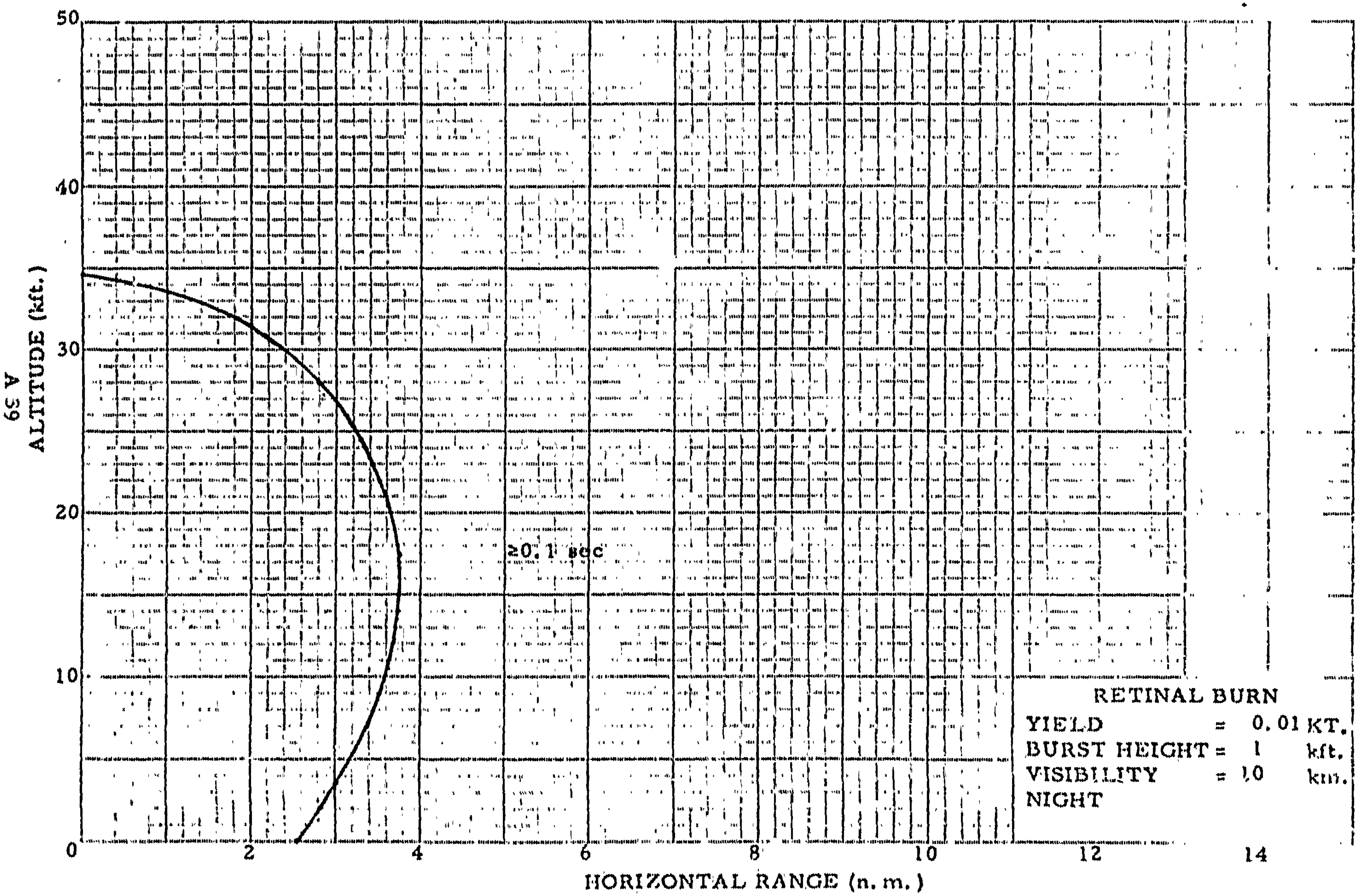


RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY
≥5.0 sec
1.0 sec
0.50 sec
0.25 sec
0.15 sec
0.10 sec
ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n. m.)
20
40
60
80
100
120
140

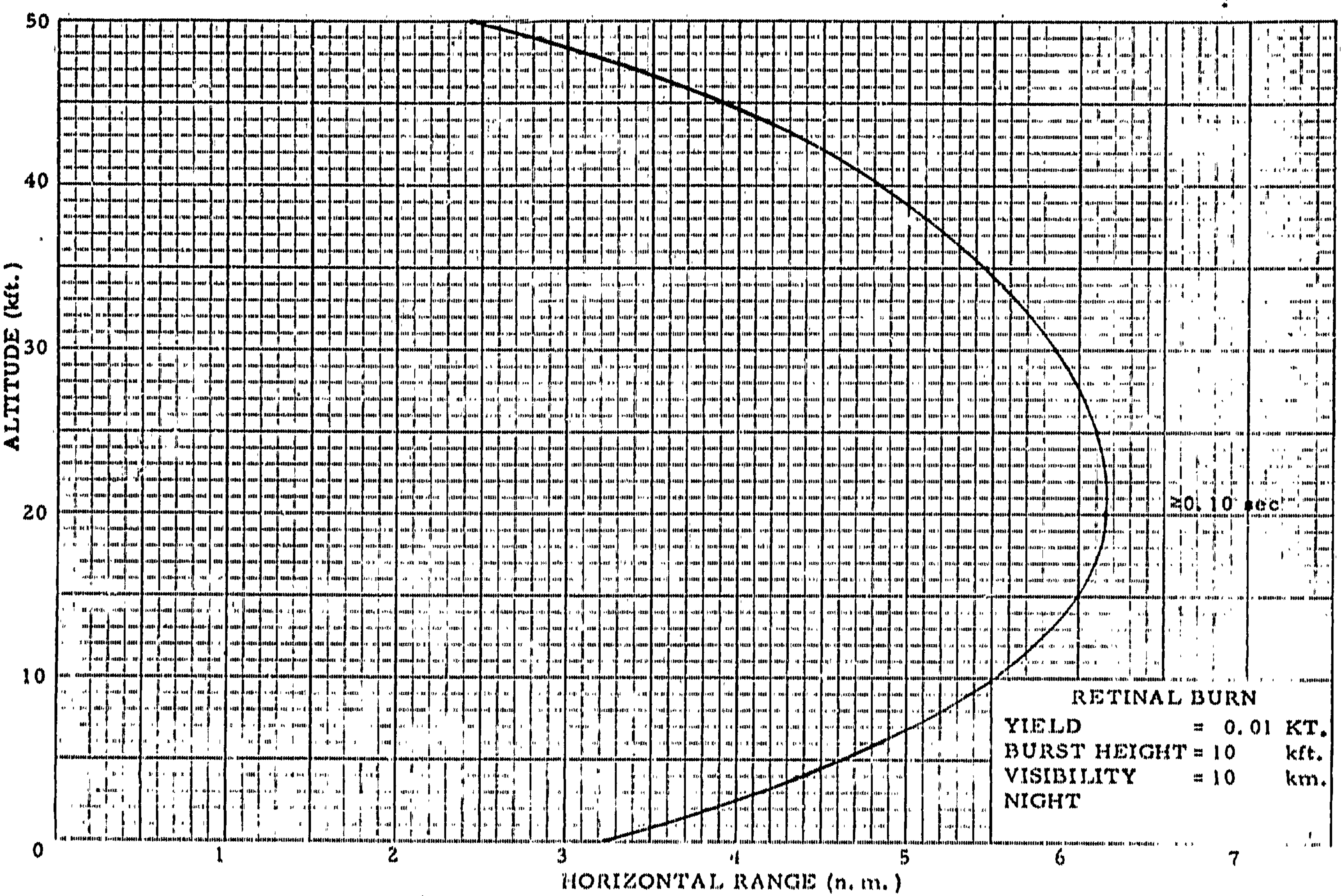


ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n. m.)
20
40
60
80
100
120
140
≥ 5.0 sec
1.0 sec
0.50 sec
0.25 sec
0.20 sec
0.15 sec
0.10 sec
RETINAL BURN
YIELD = 10000KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100km.
DAY

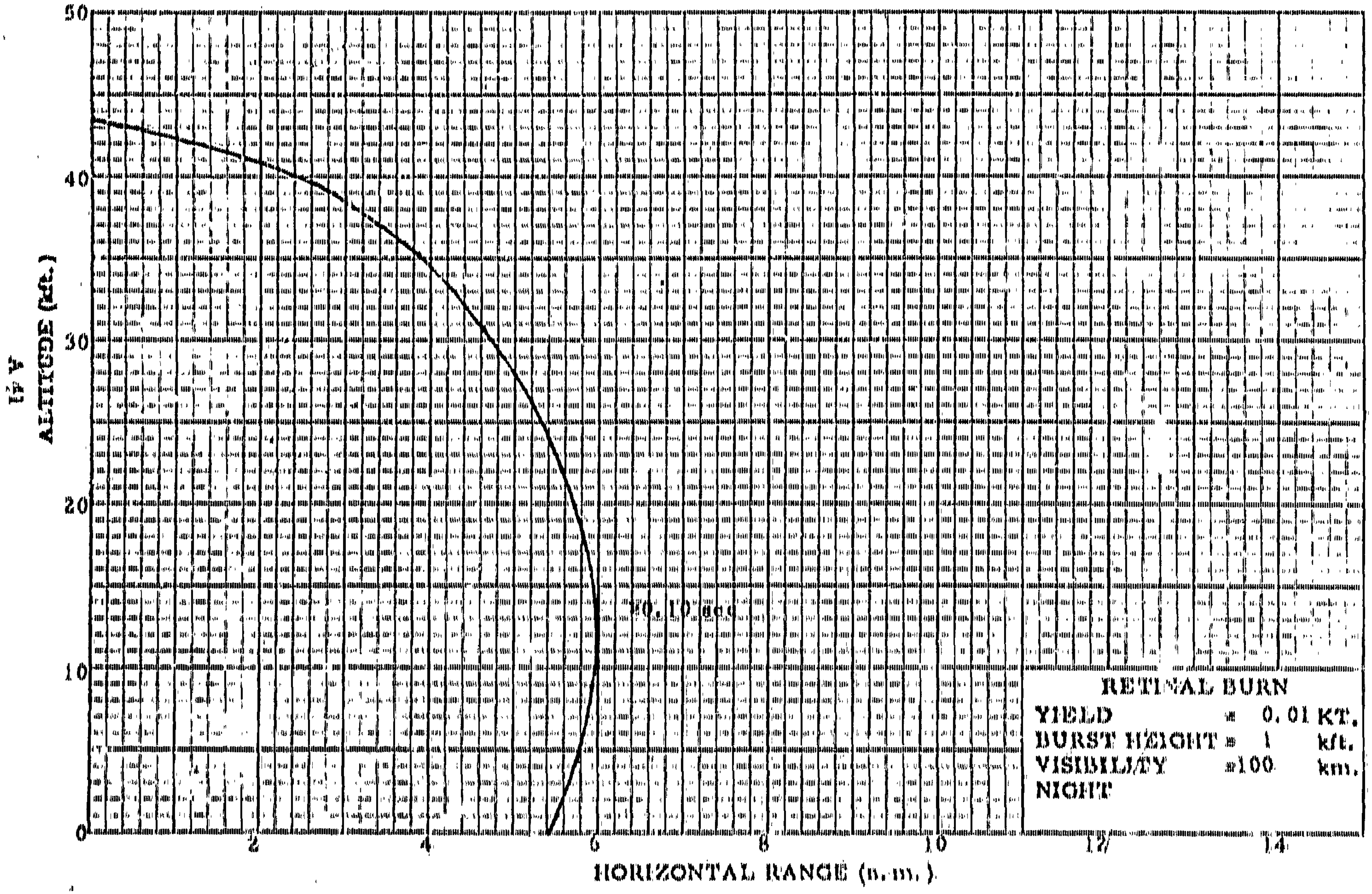

RETINAL BURN
YIELD =10, 000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY
≥ 5.0 sec
1.0 sec
0.50 sec
0.25 sec
0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
50
100
150
200
250
300
350

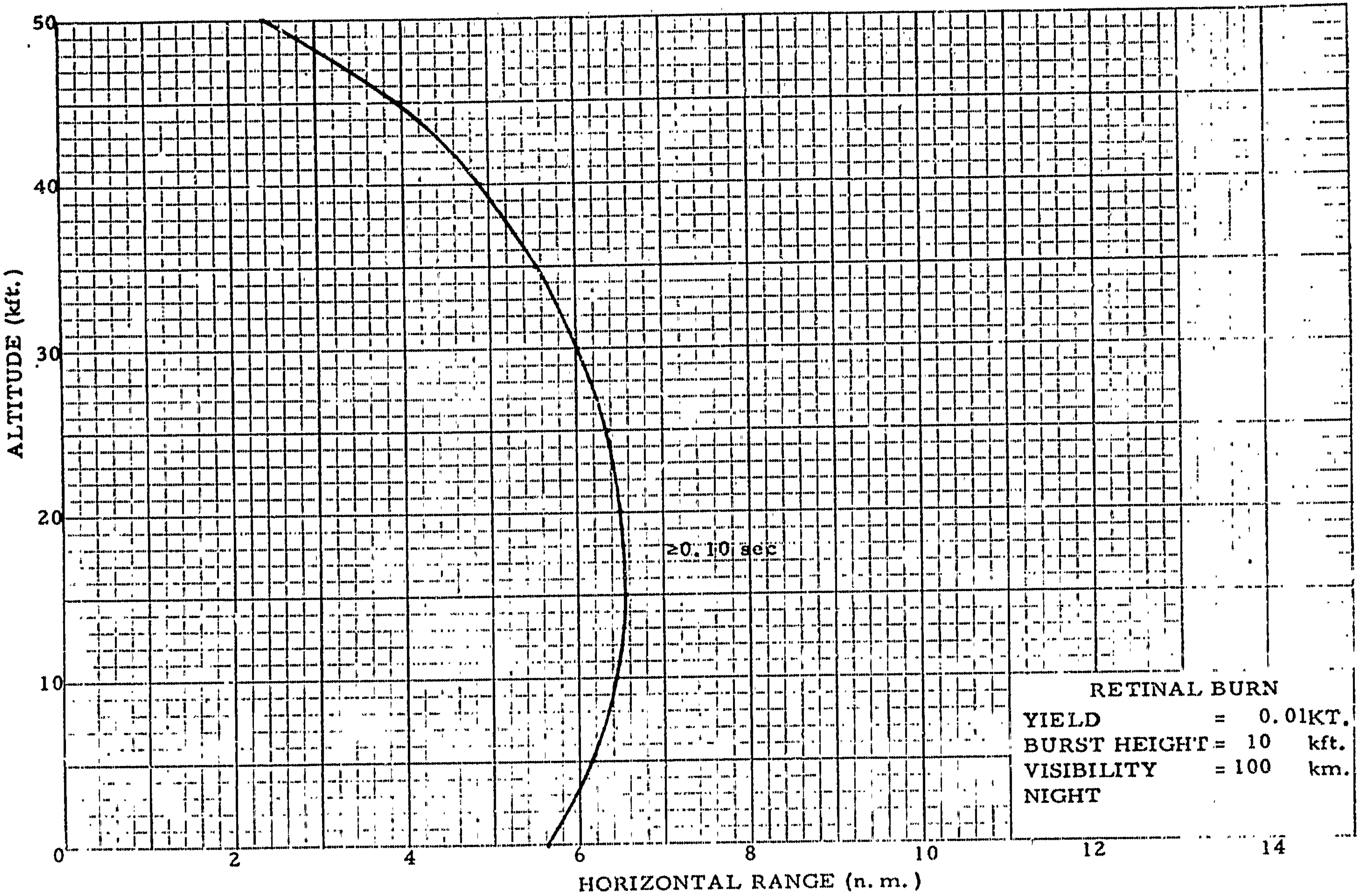

ALTITUDE (kft.)
50
40
30
20
10
0
2
4
6
8
10
12
14
HORIZONTAL RANGE (n. m.)
≥0. 1 sec
RETINAL BURN
YIELD = 0. 01 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
NIGHT

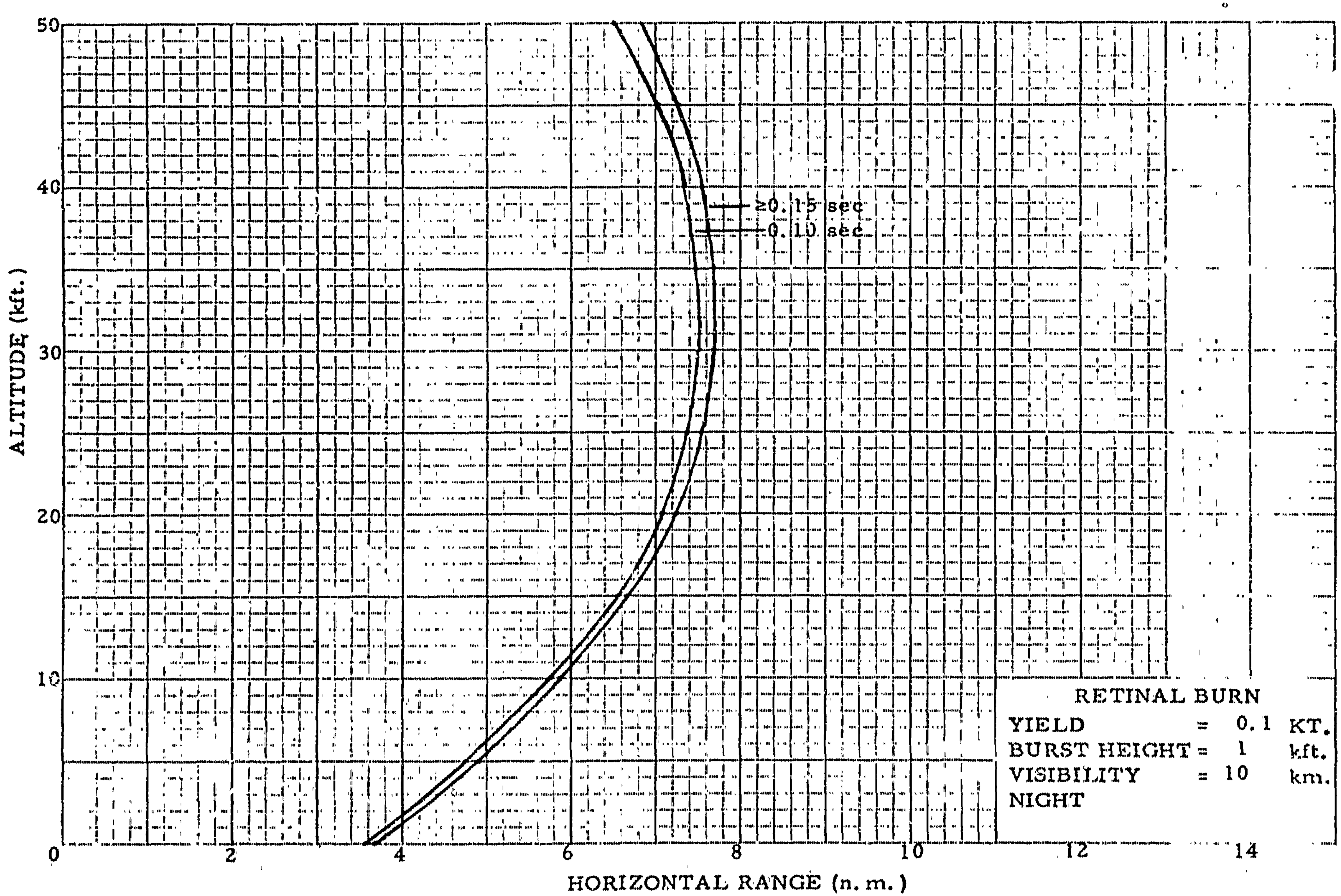
A 39

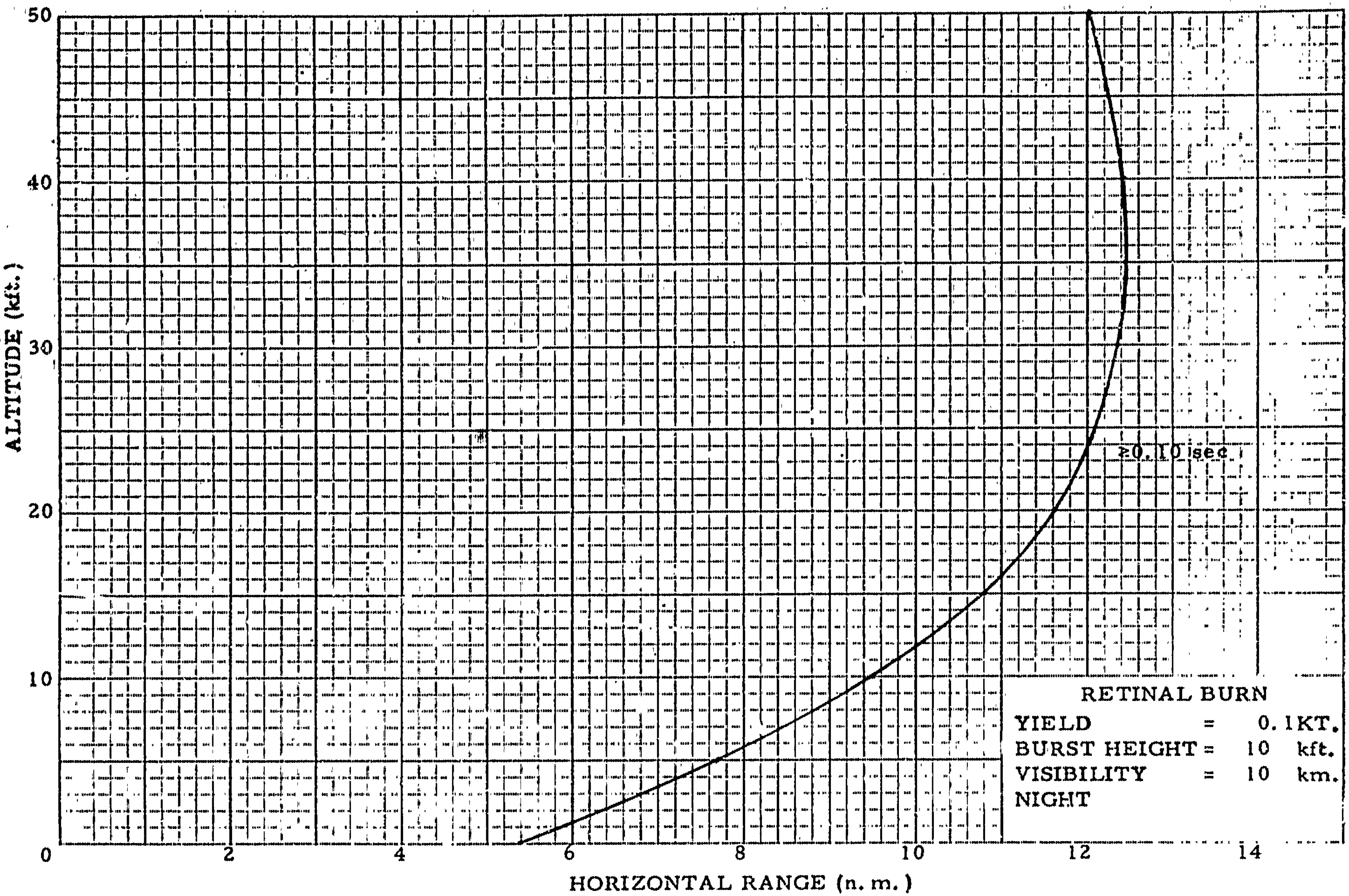


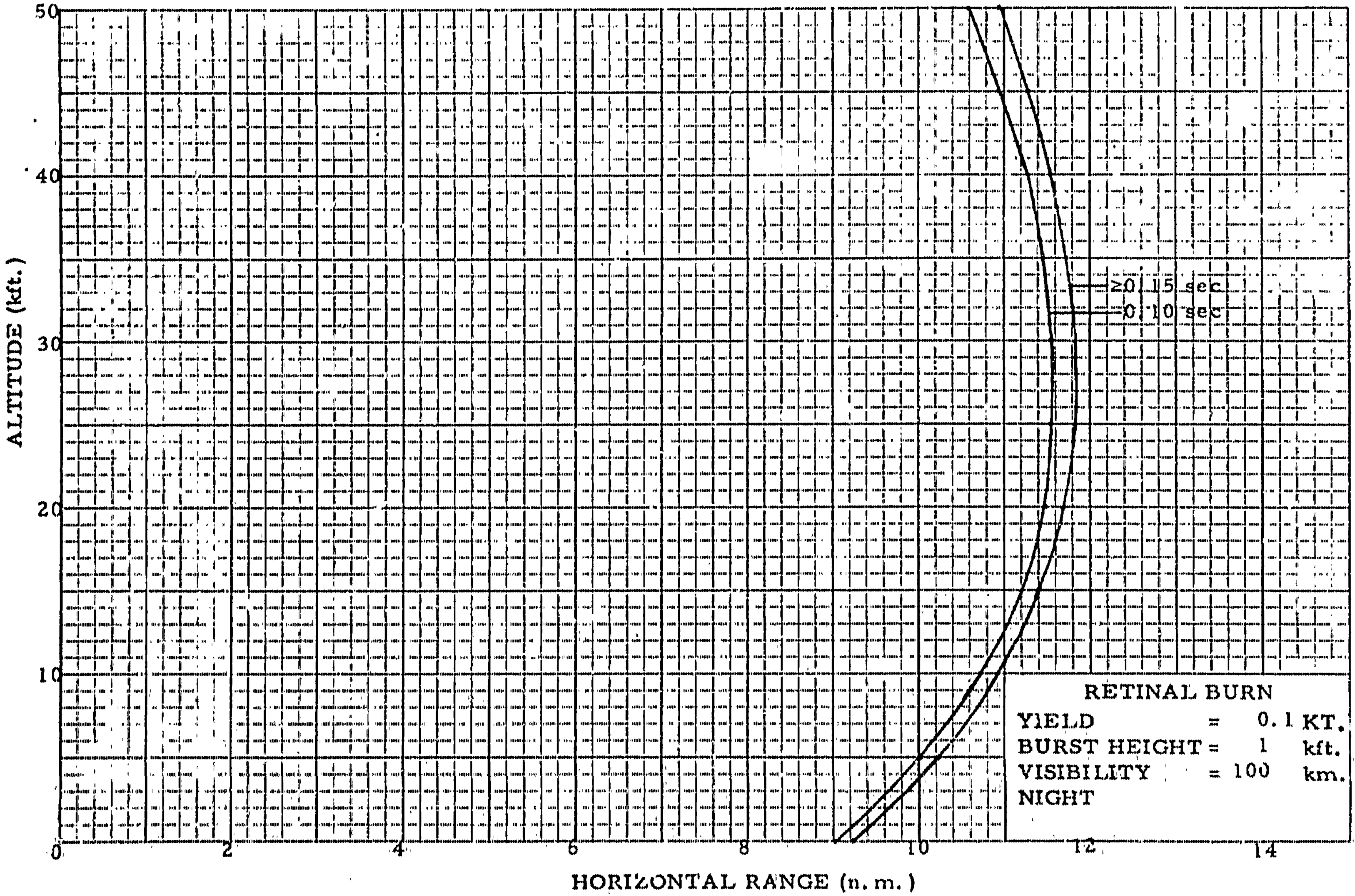
ALTITUDE (kft.)
50
40
30
20
10
0
1
2
3
4
5
6
7
HORIZONTAL RANGE (n. m.)
≥0.10 sec
RETINAL BURN
YIELD = 0.01 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
NIGHT

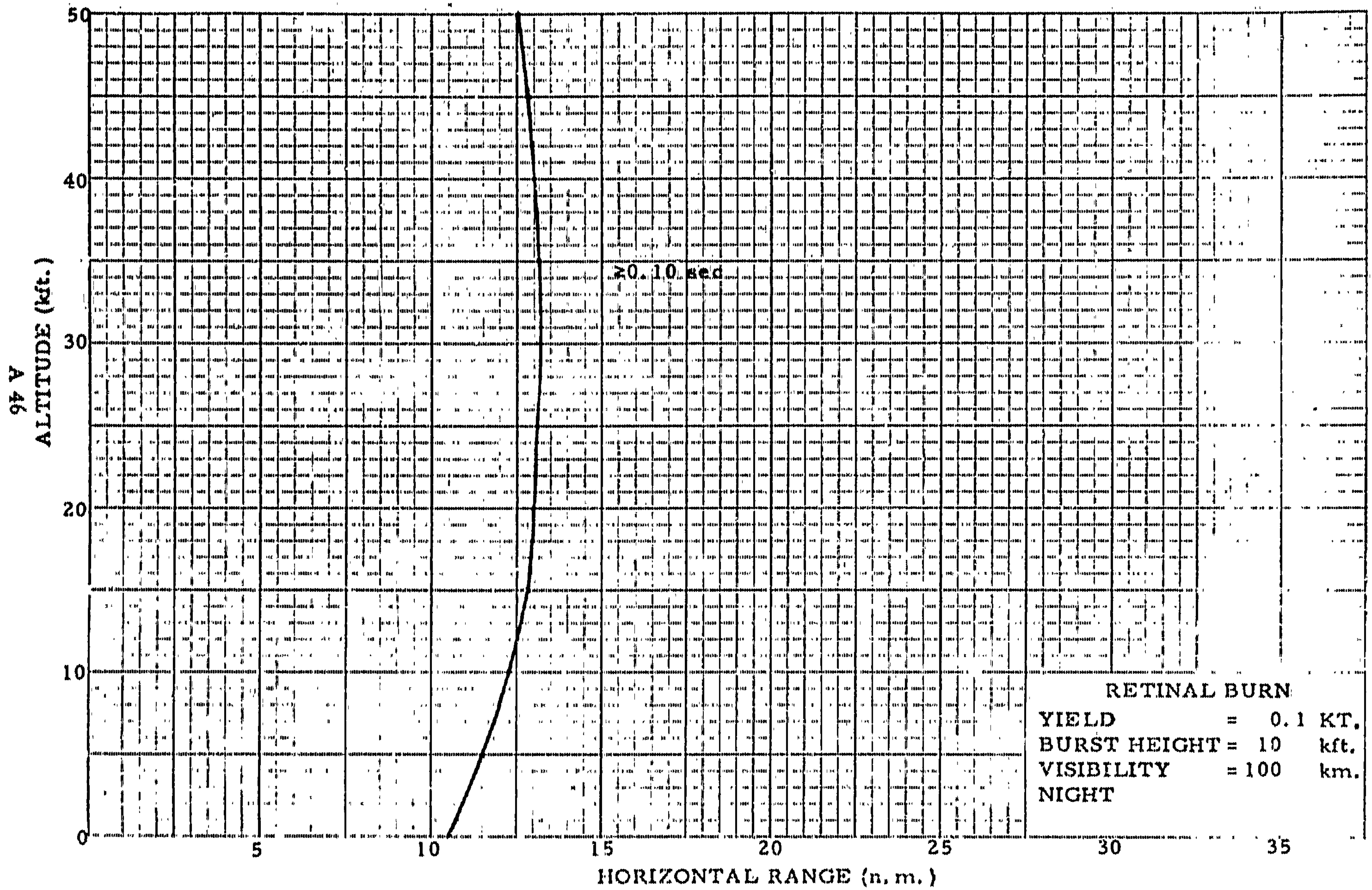

ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n.m.)
2
4
6
8
10
12
14
RETINAL BURN
YIELD = 0.01 KT.
BURST HEIGHT = 1 kft.
VISIBILITY =100 km.
NIGHT

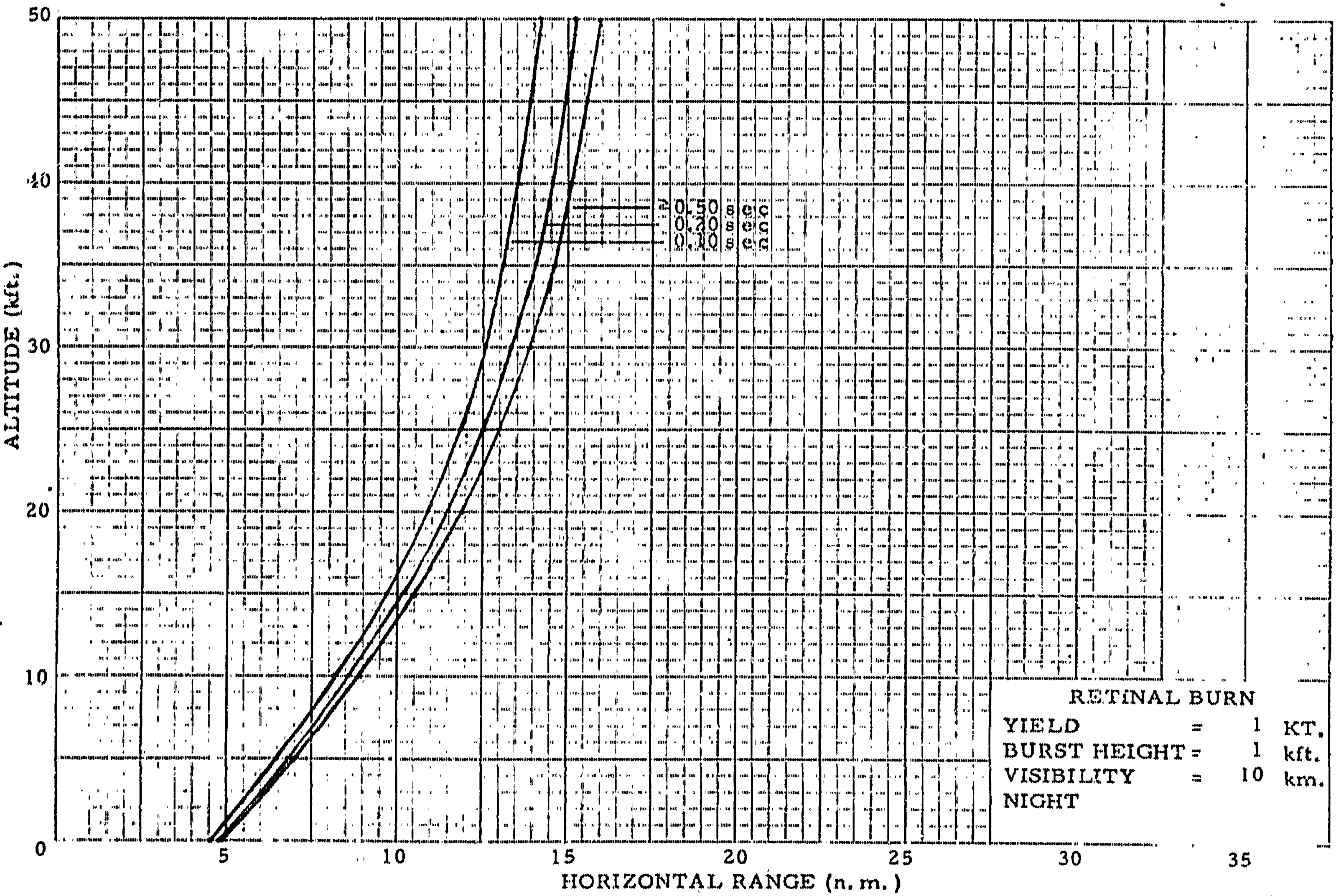

RETINAL BURN
YIELD = 0.01KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT
≥0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
2
4
6
8
10
12
14
10
20
30
40
50


RETINAL BURN
YIELD = 0.1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
NIGHT
≥0.15 sec
0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
2
4
6
8
10
12
14

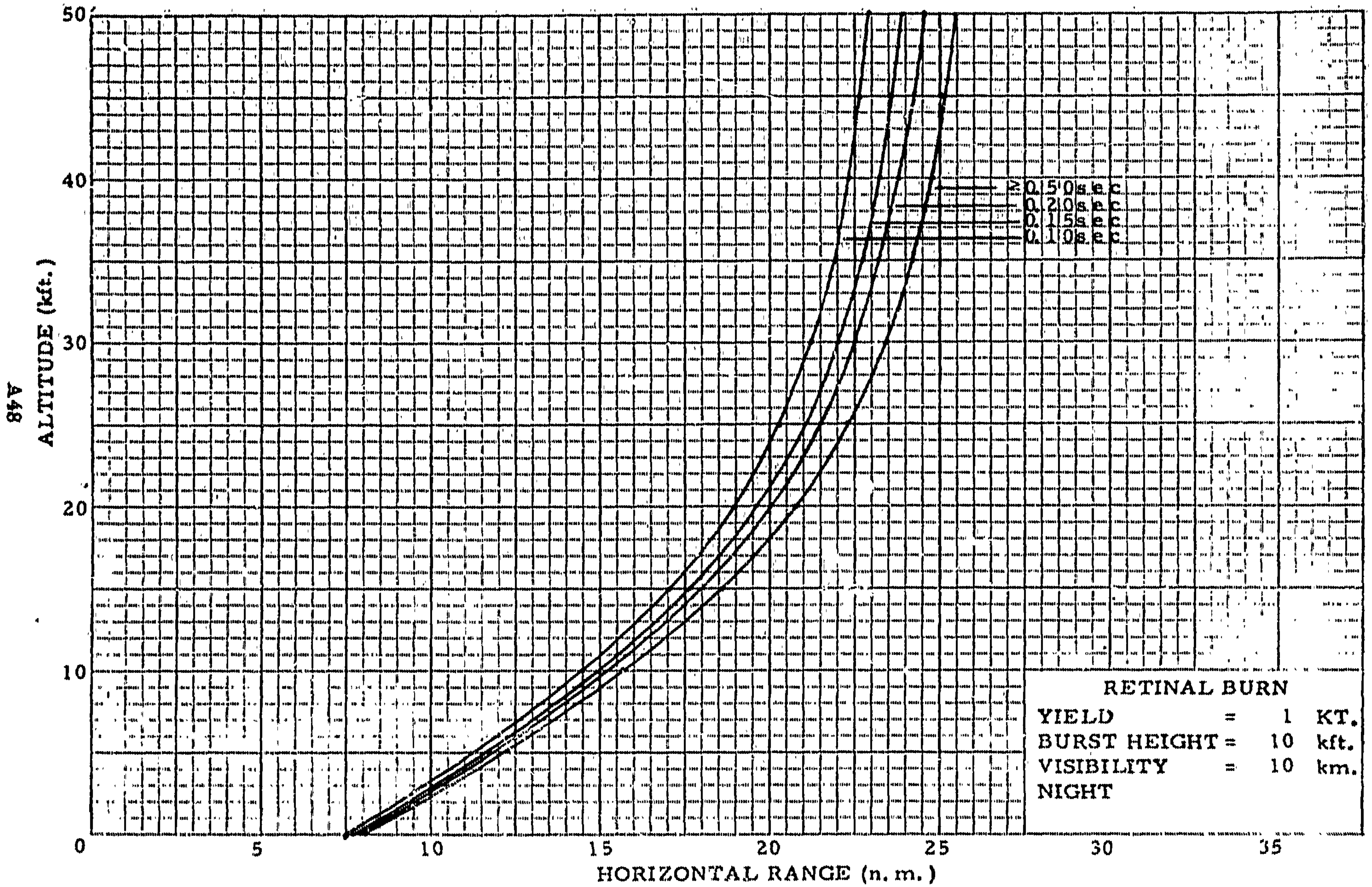

RETINAL BURN
YIELD = 0.1KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
NIGHT
≥0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
2
4
6
8
10
12
14


≥0.15 sec
0.10 sec
RETINAL BURN
YIELD = 0.1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
2
4
6
8
10
12
14
10
20
30
40
50

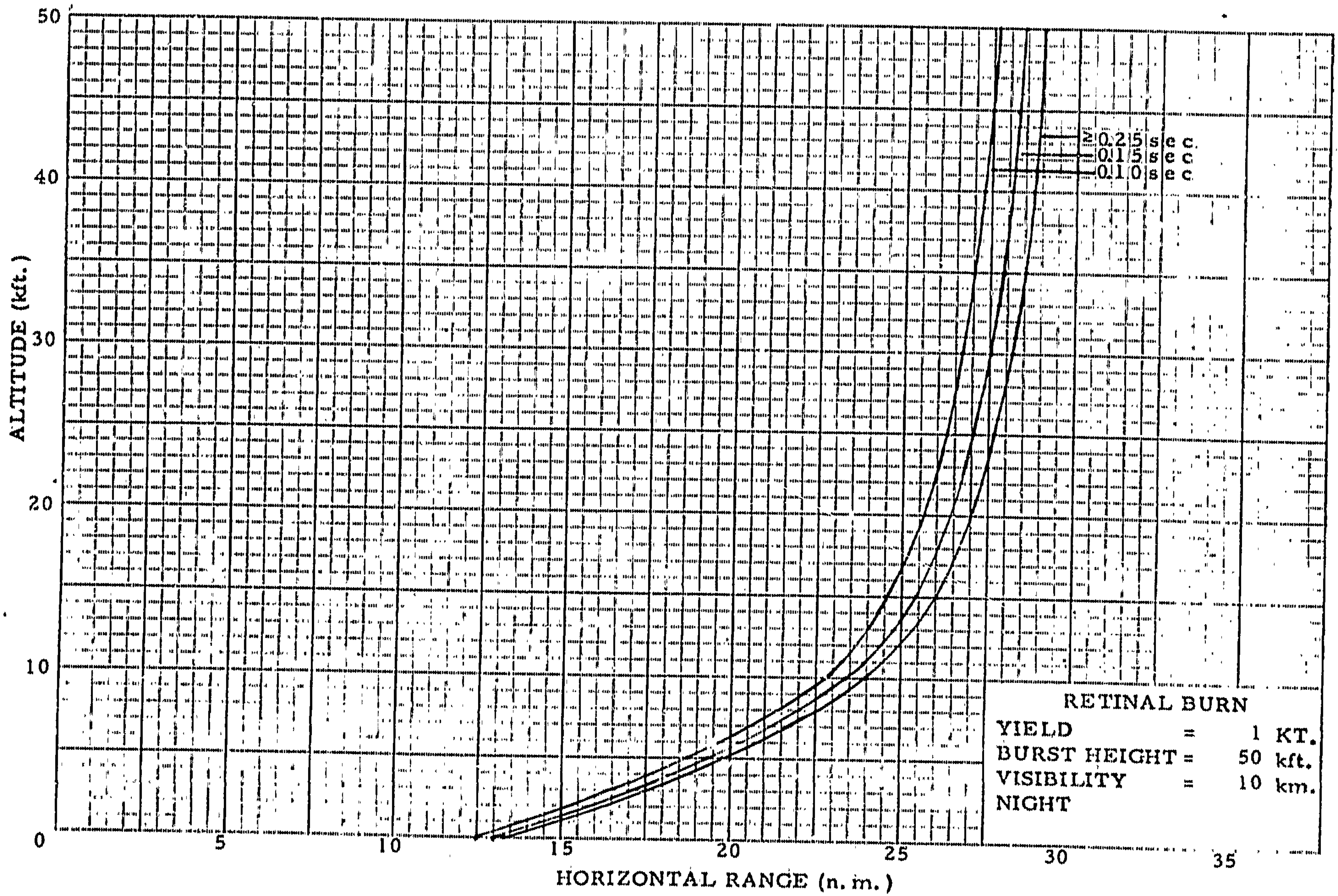

ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n. m.)
5
10
15
20
25
30
35
≥0.10 sec
RETINAL BURN
YIELD = 0.1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT



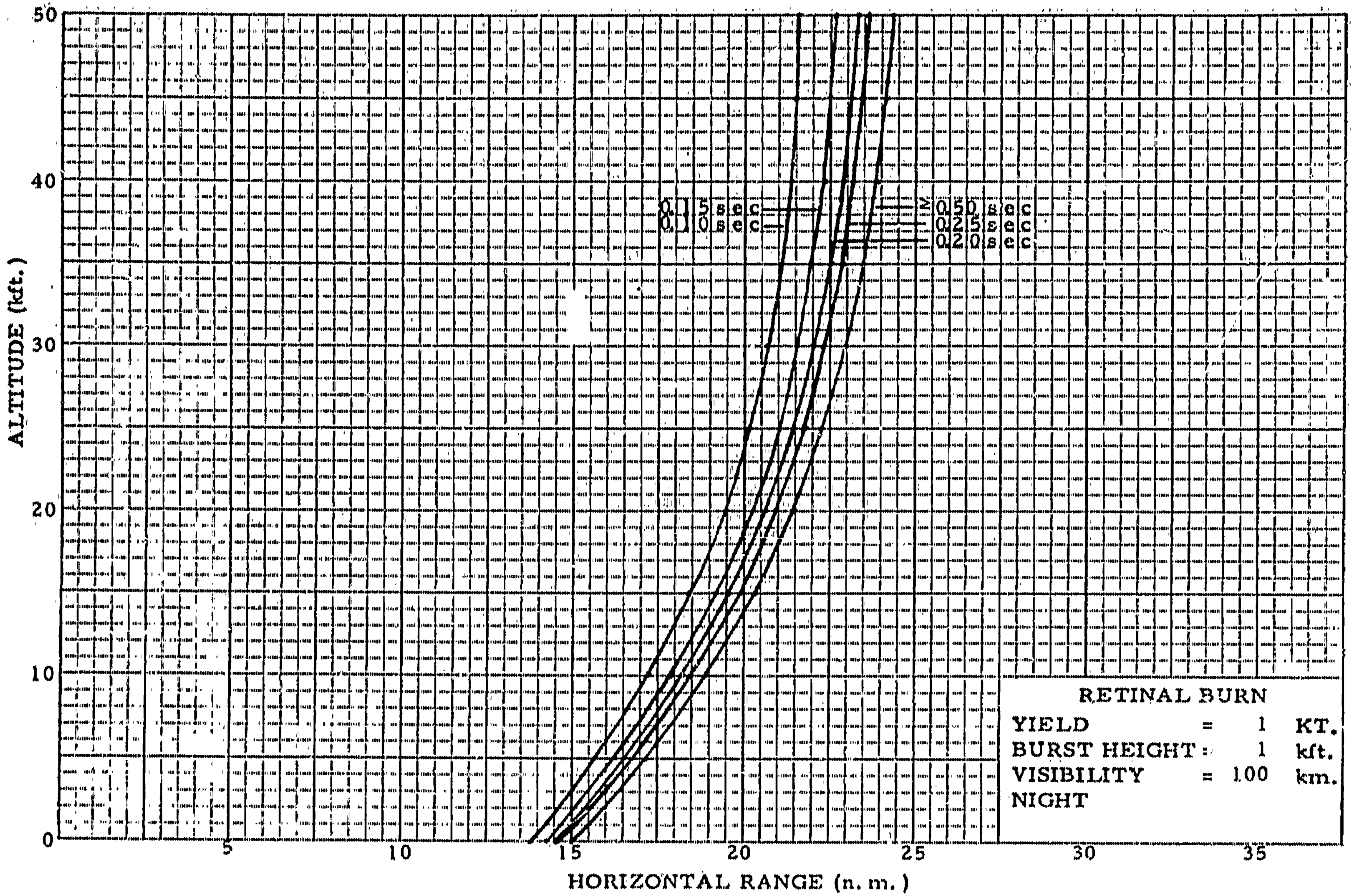
50
40
30
20
10
0
5
10
15
20
25
30
35
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0.50 sec
0.20 sec
0.10 sec
RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
NIGHT



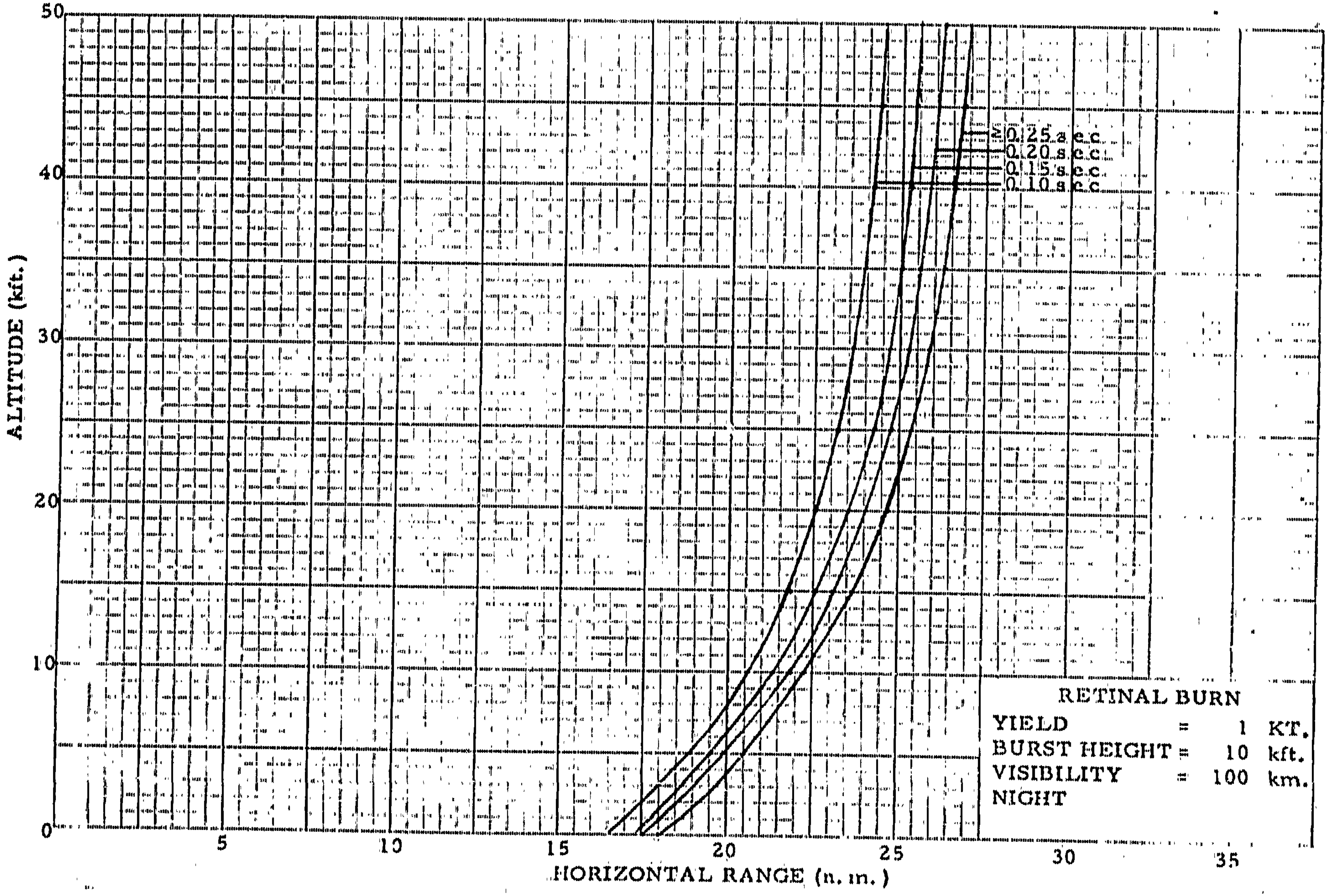
50
40
30
20
10
0
ALTITUDE (kft.)
5
10
15
20
25
30
35
HORIZONTAL RANGE (n. m.)
≥0.50sec
0.20sec
0.15sec
0.10sec
RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
NIGHT

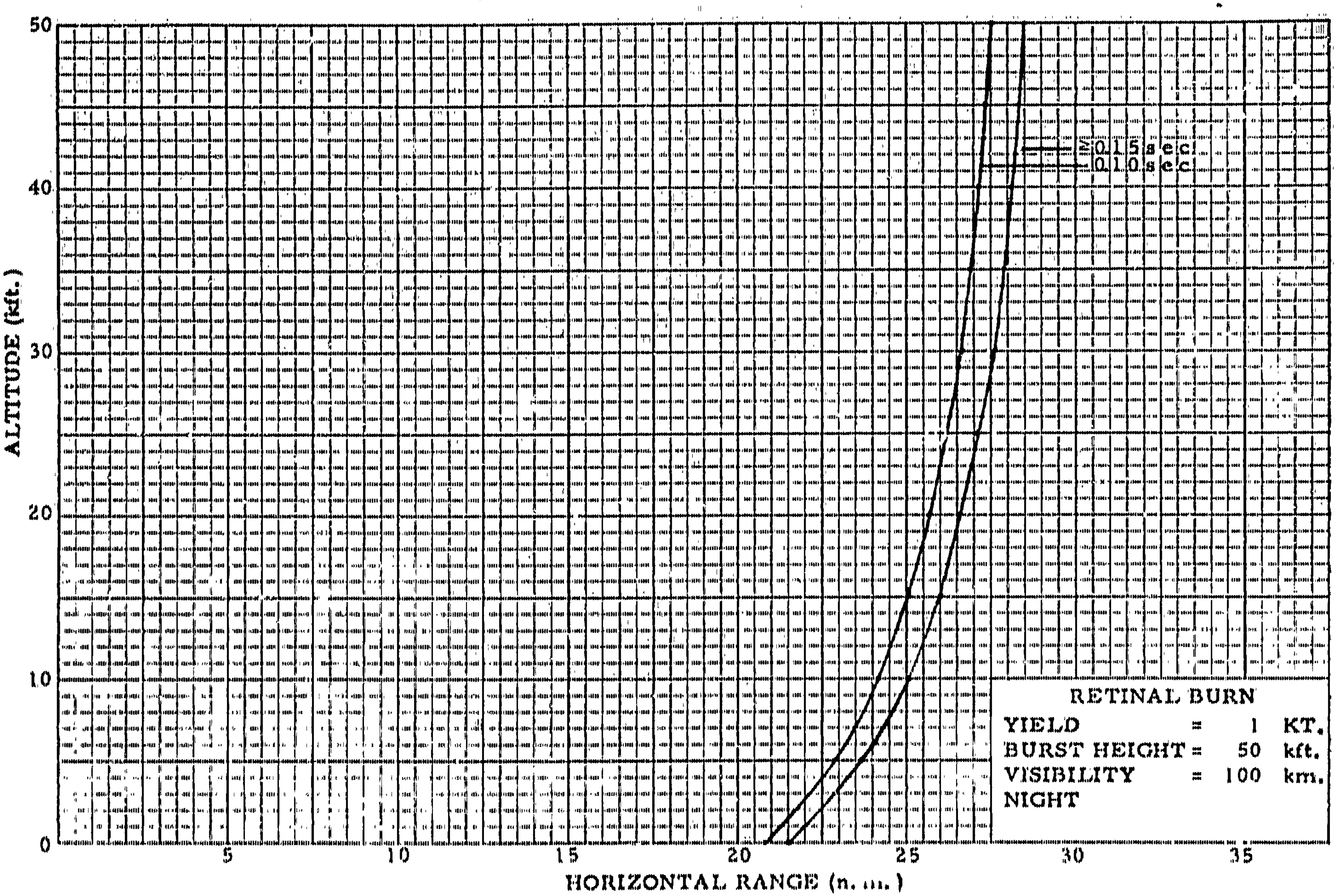


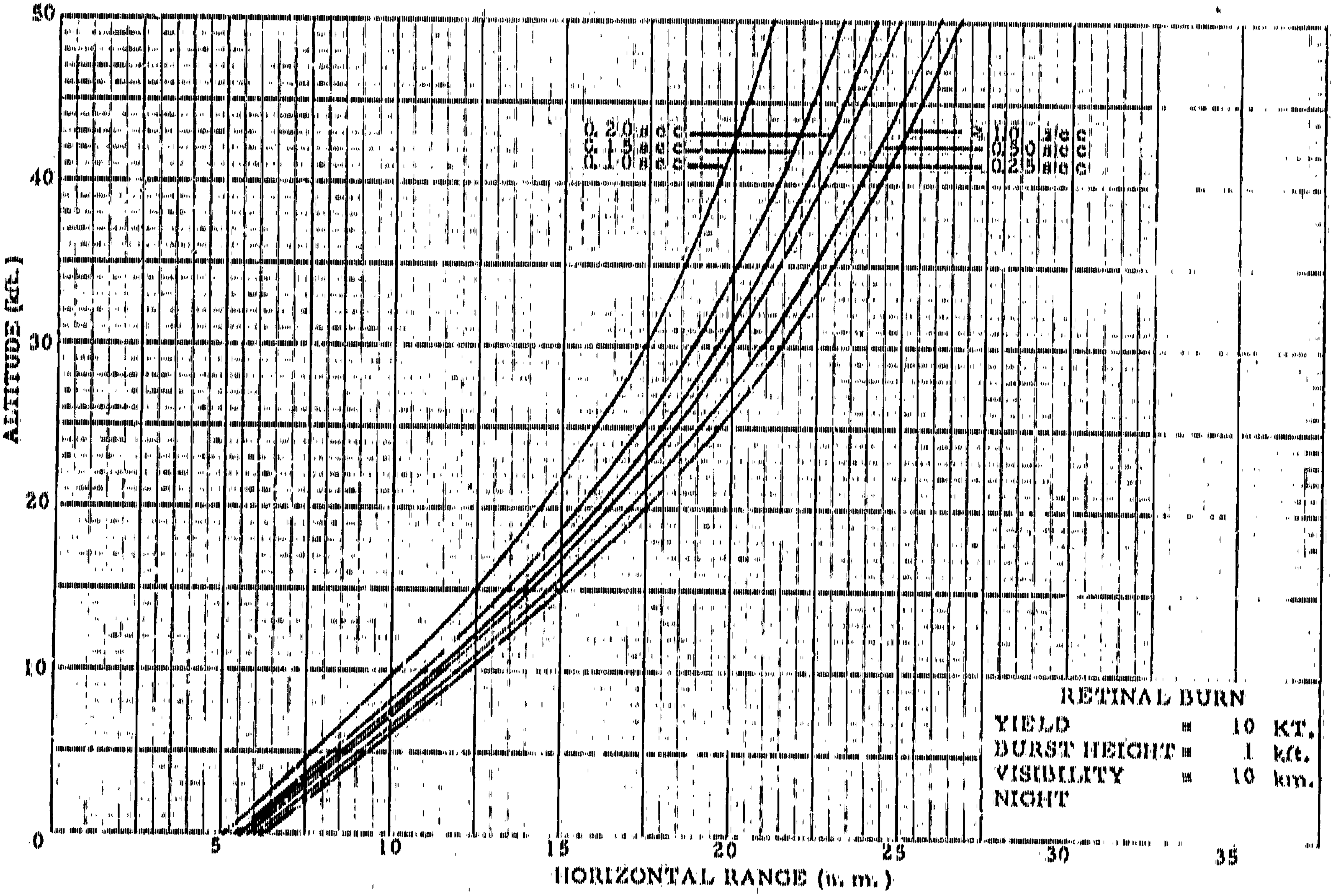
50
40
30
20
10
0
ALTITUDE (kft.)
5
10
15
20
25
30
35
HORIZONTAL RANGE (n. m.)
≥0.25 sec
0.15 sec
0.10 sec
RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
NIGHT

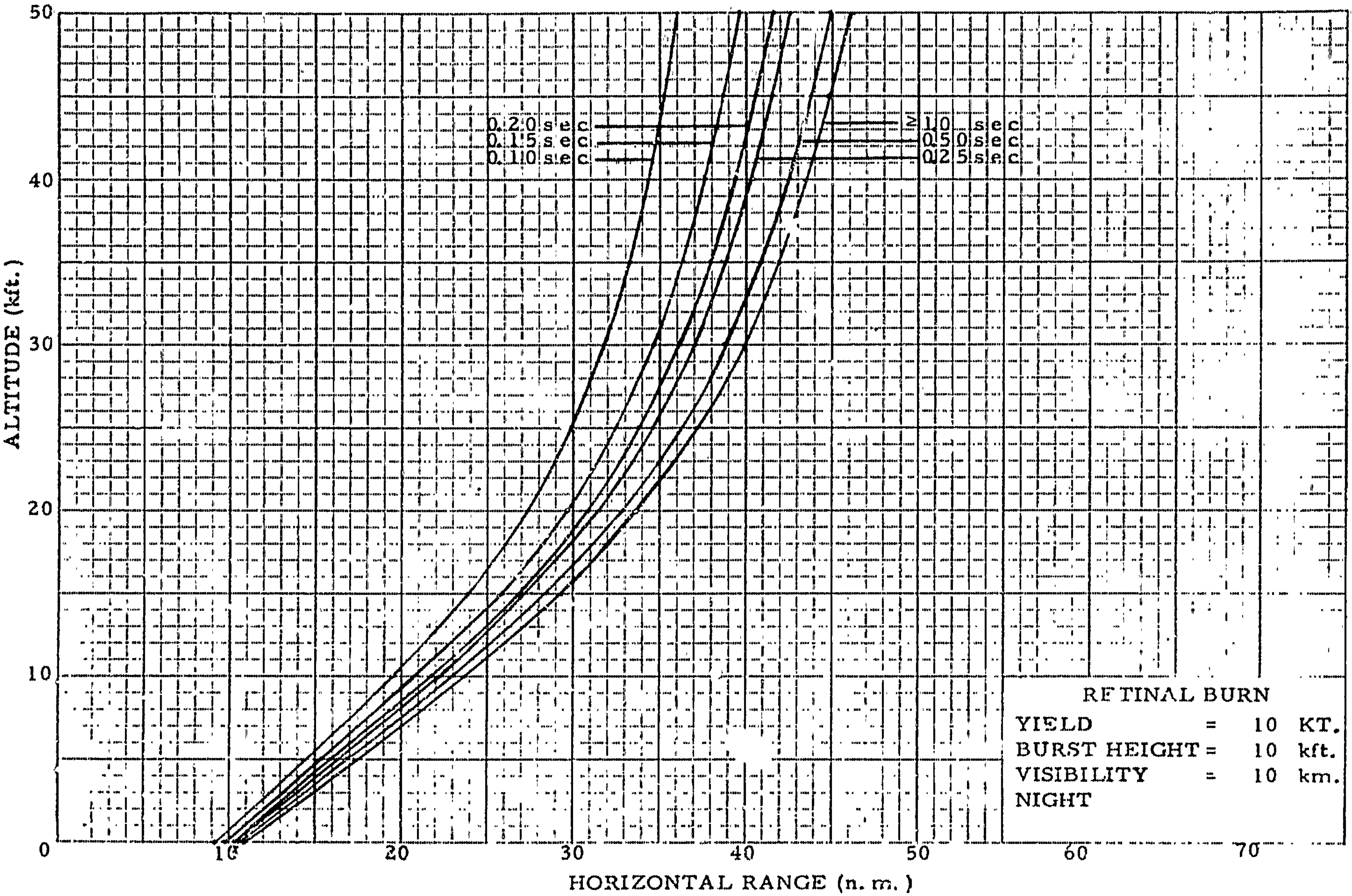


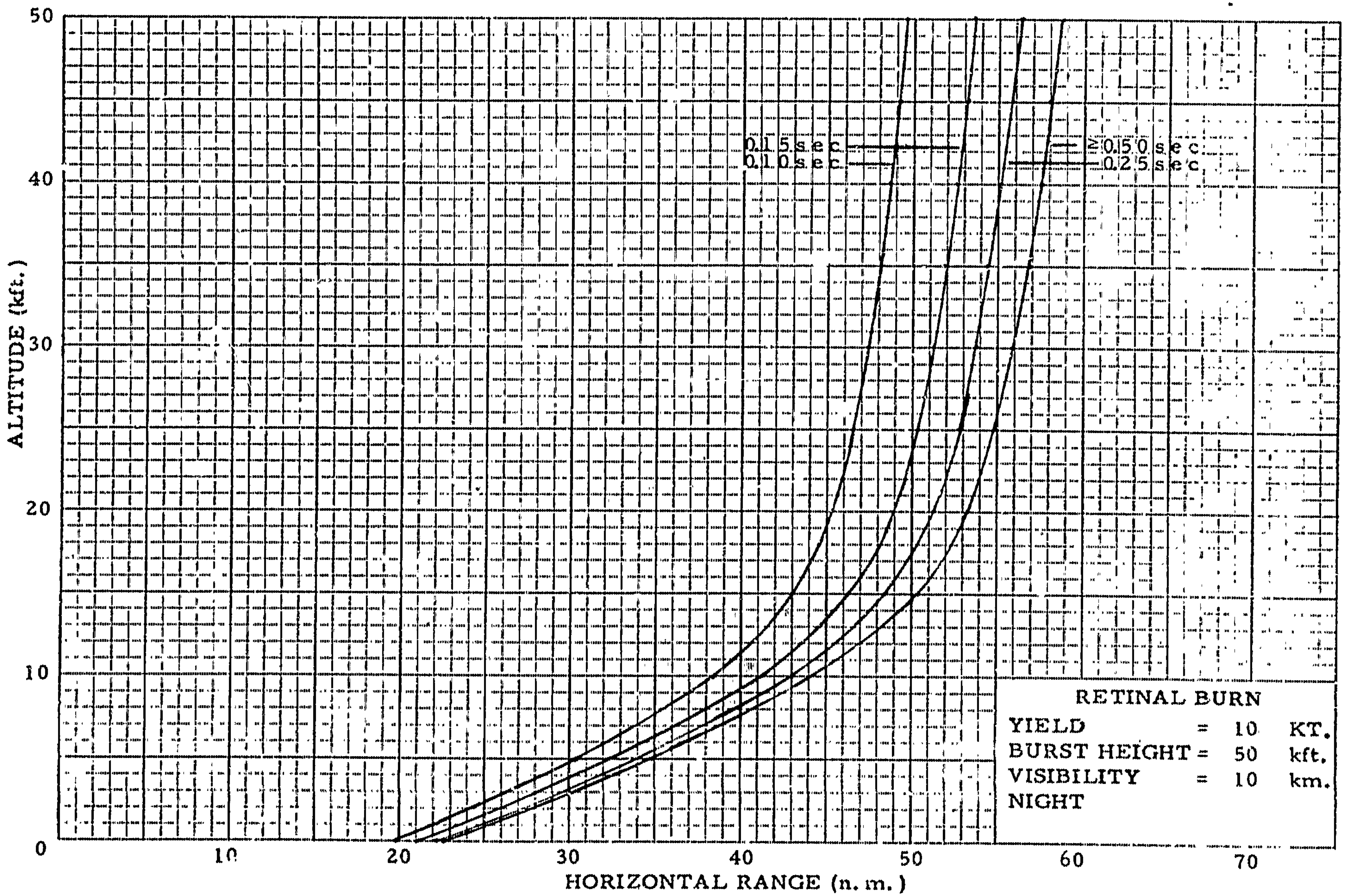
ALTITUDE (kft.)
50
40
30
20
10
0
5
10
15
20
25
30
35
HORIZONTAL RANGE (n. m.)
0.15 sec
0.10 sec
≥ 0.50 sec
0.25 sec
0.20 sec
RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT

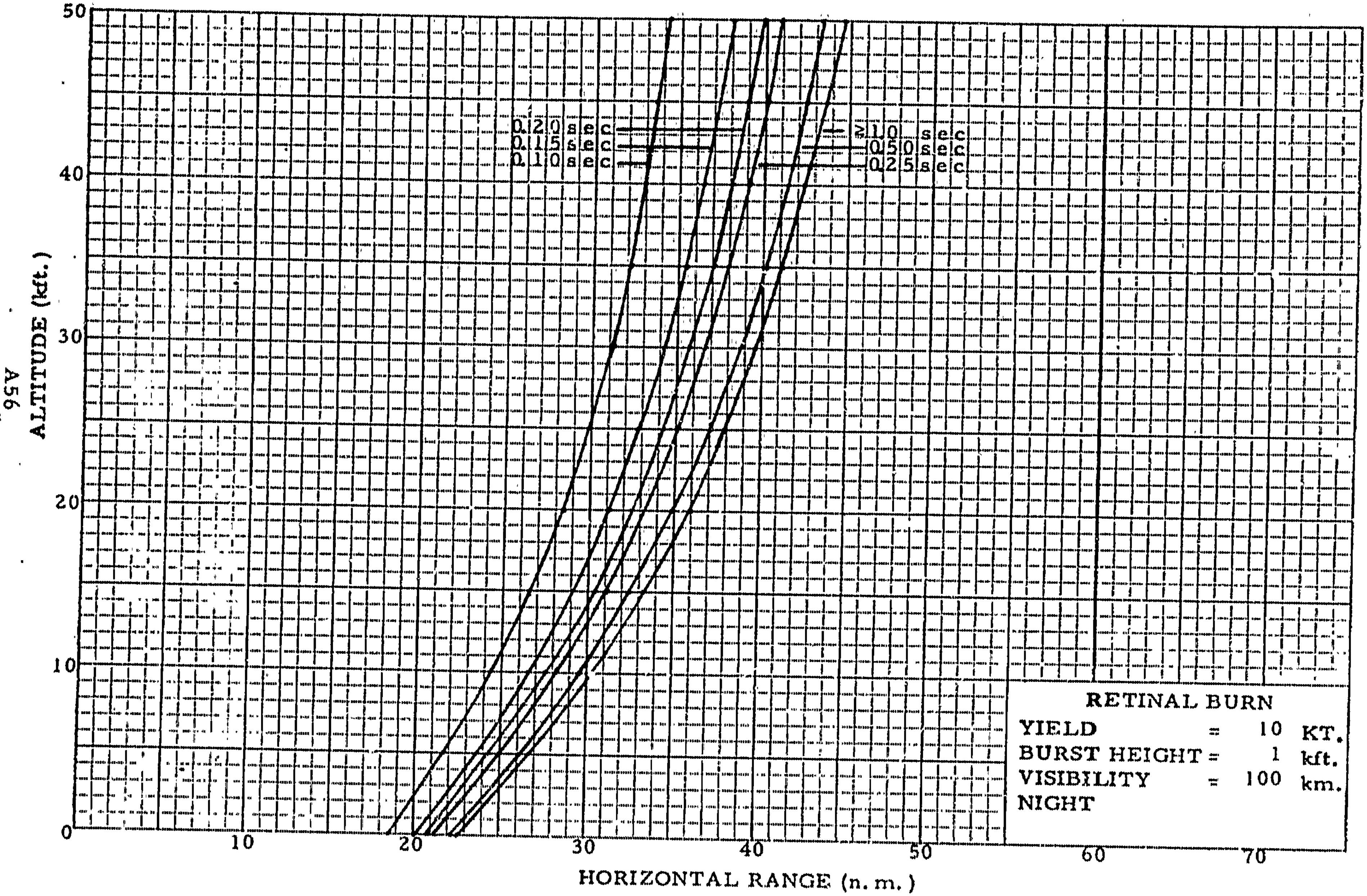

≥0.25 sec
0.20 sec
0.15 sec
0.10 sec
RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. mi.)
0
10
20
30
40
50
5
10
15
20
25
30
35


RETINAL BURN
YIELD = 1 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT
015 sec
010 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. mi.)
0
10
20
30
40
50
5
15
25
35

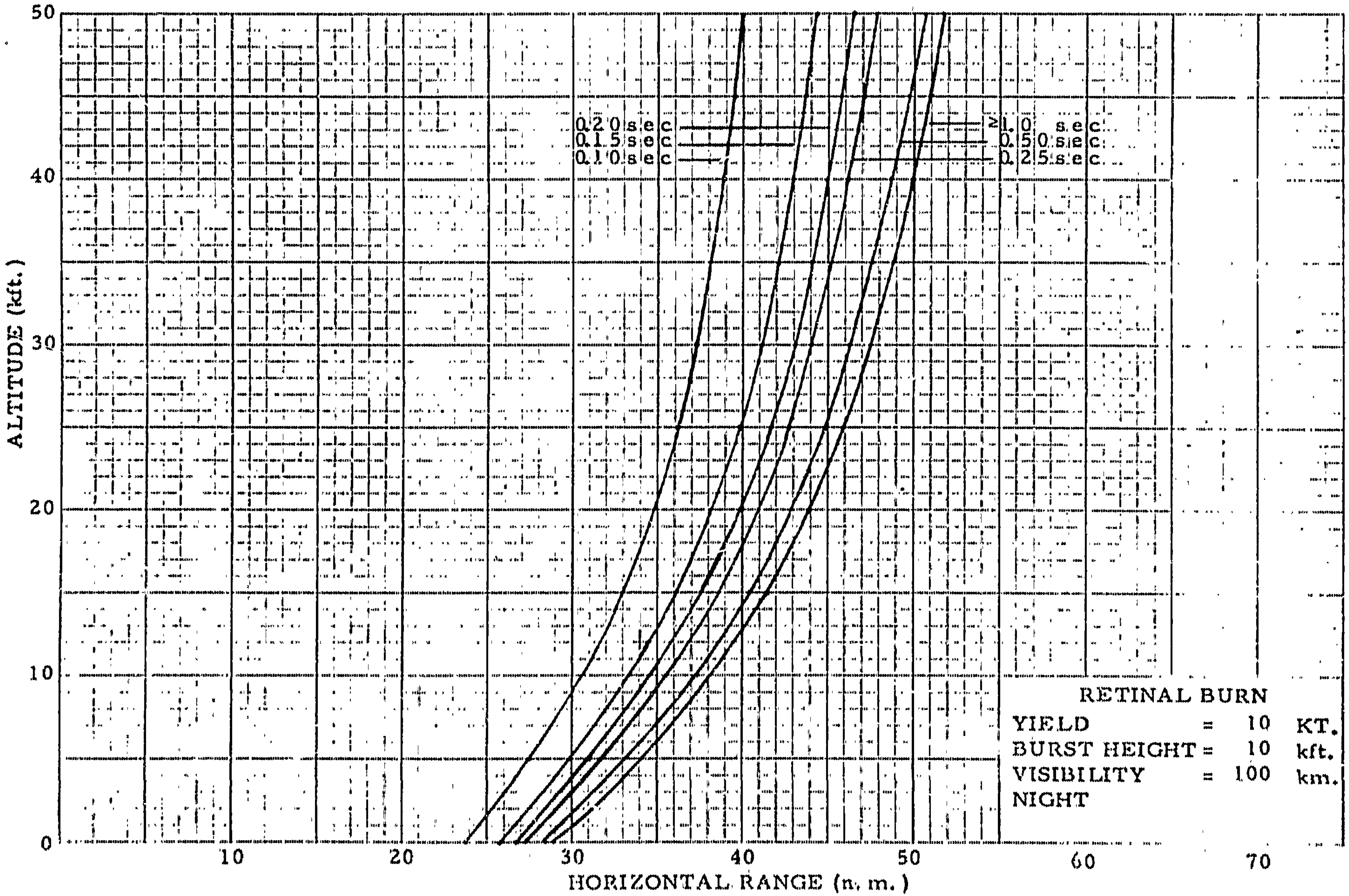

RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
NIGHT
0.20 sec
0.15 sec
0.10 sec
1.0 sec
0.50 sec
0.25 sec
ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n. m.)
5
10
15
20
25
30
35

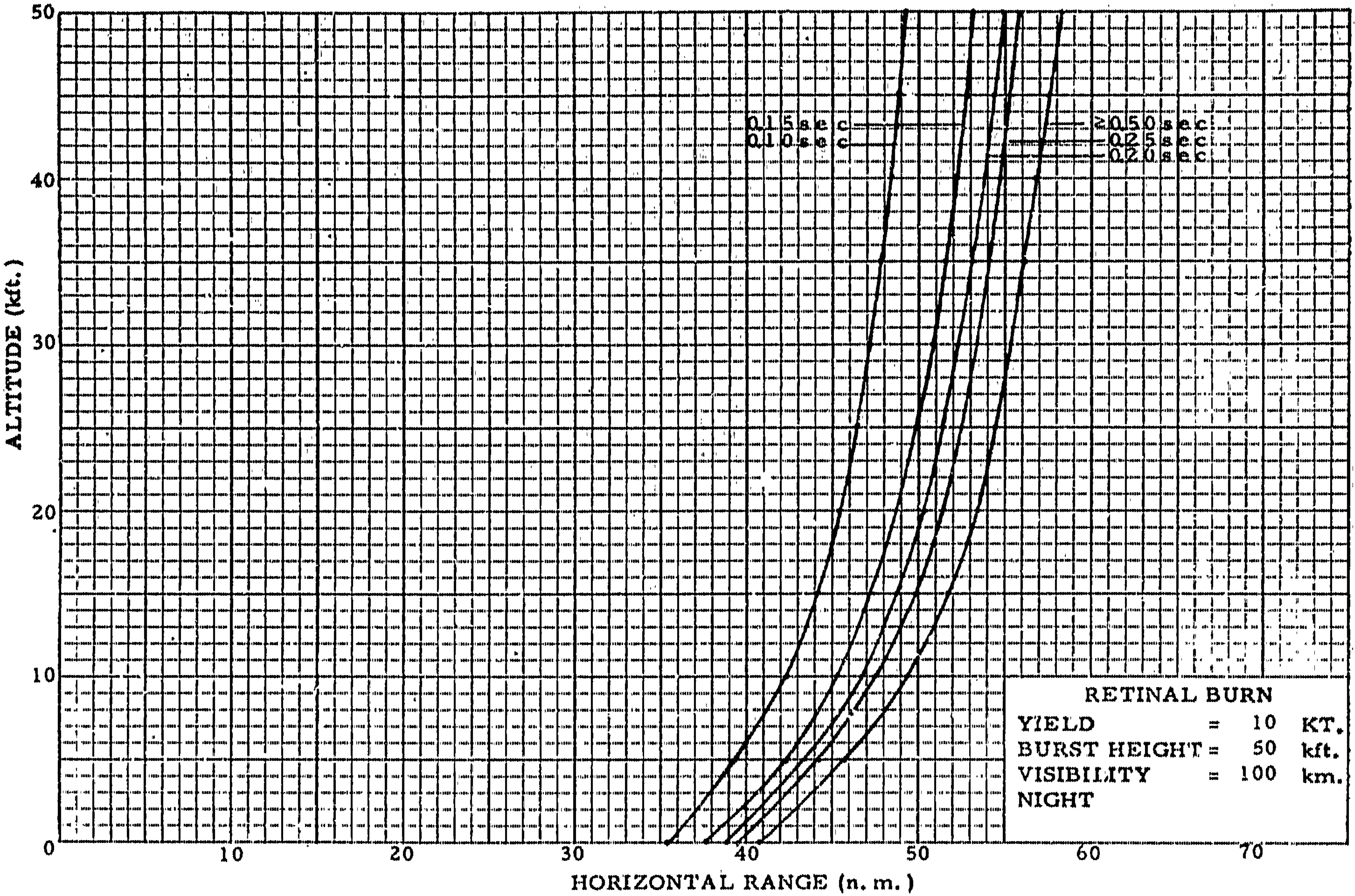

0.20 sec
0.15 sec
0.10 sec
≥1.0 sec
0.50 sec
0.25 sec
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70


0.15 sec
0.10 sec
≥0.50 sec
0.25 sec
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70

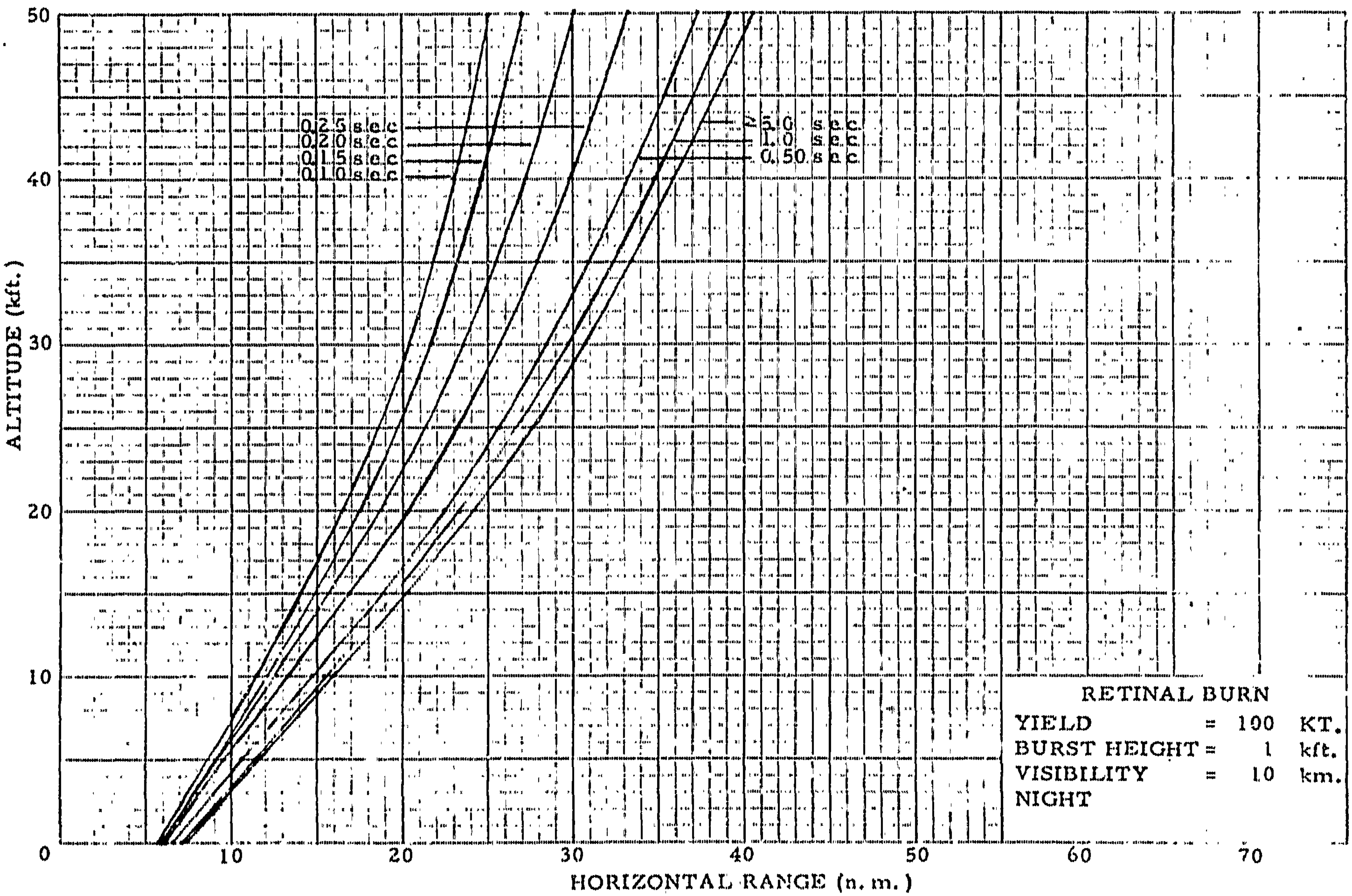


0.20 sec
0.15 sec
0.10 sec
≥1.0 sec
0.50 sec
0.25 sec
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70

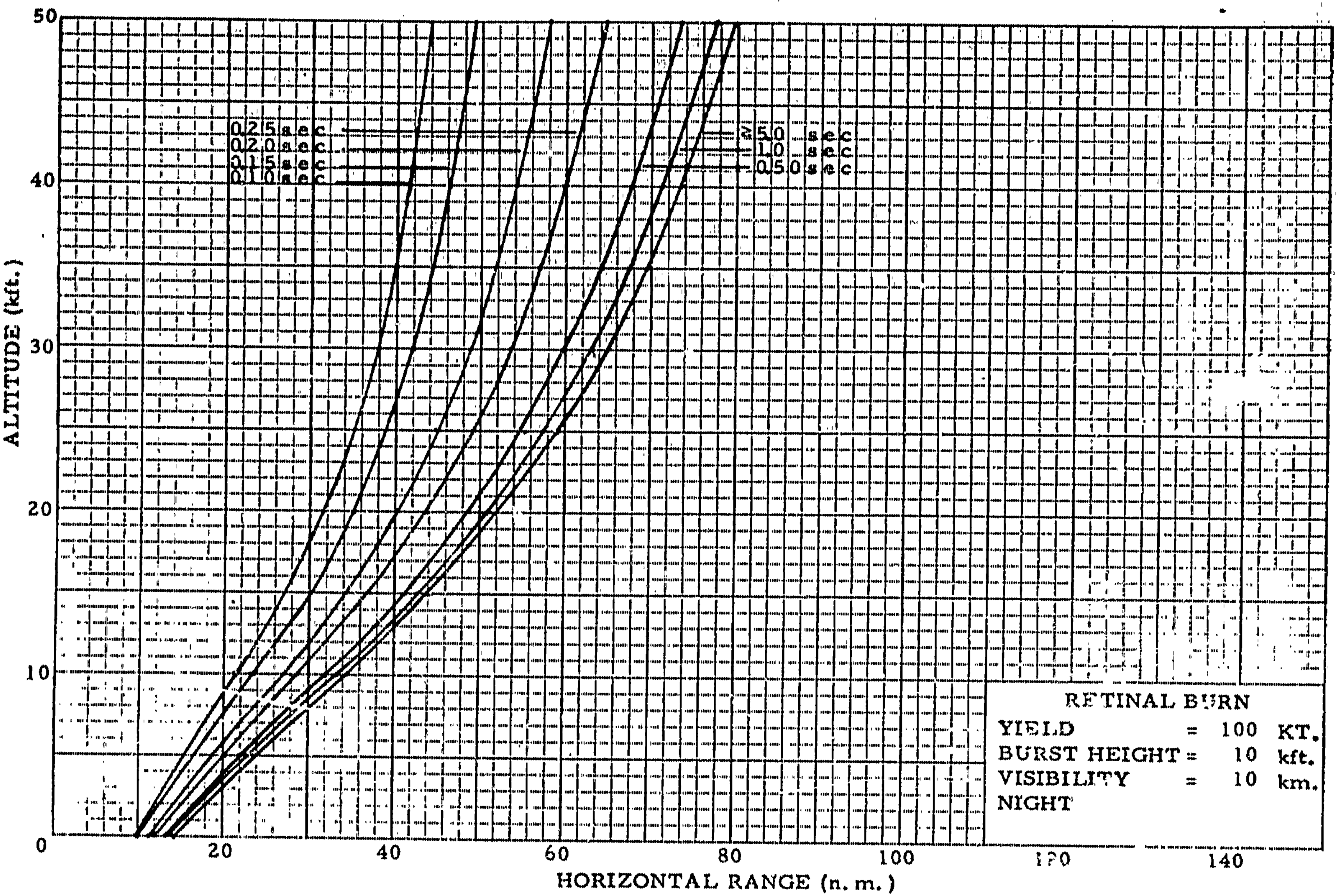

RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT
0.20 sec
0.15 sec
0.10 sec
≥1.0 sec
0.50 sec
0.25 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70

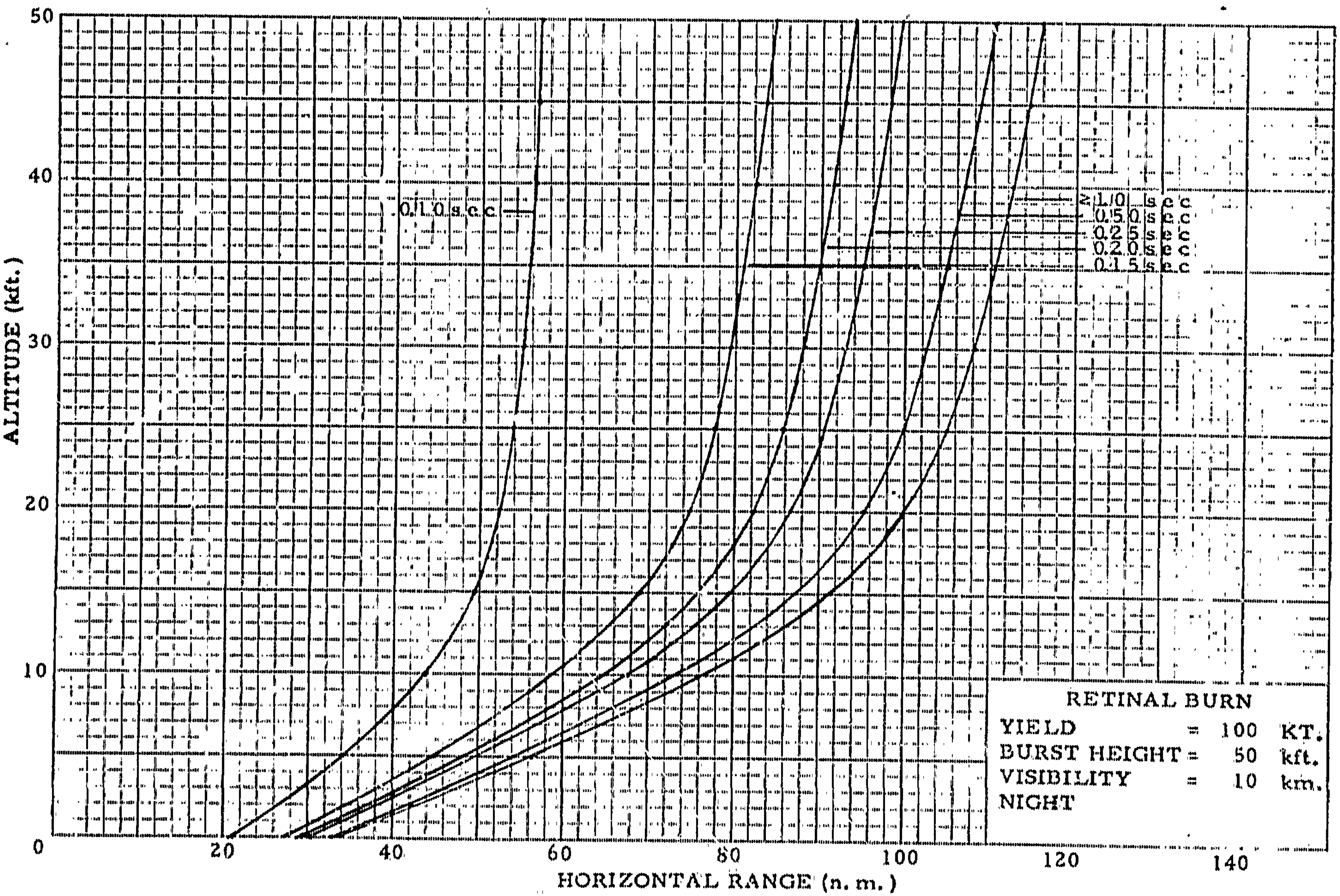


0.15 sec
0.10 sec
≥0.50 sec
0.25 sec
0.20 sec
RETINAL BURN
YIELD = 10 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70

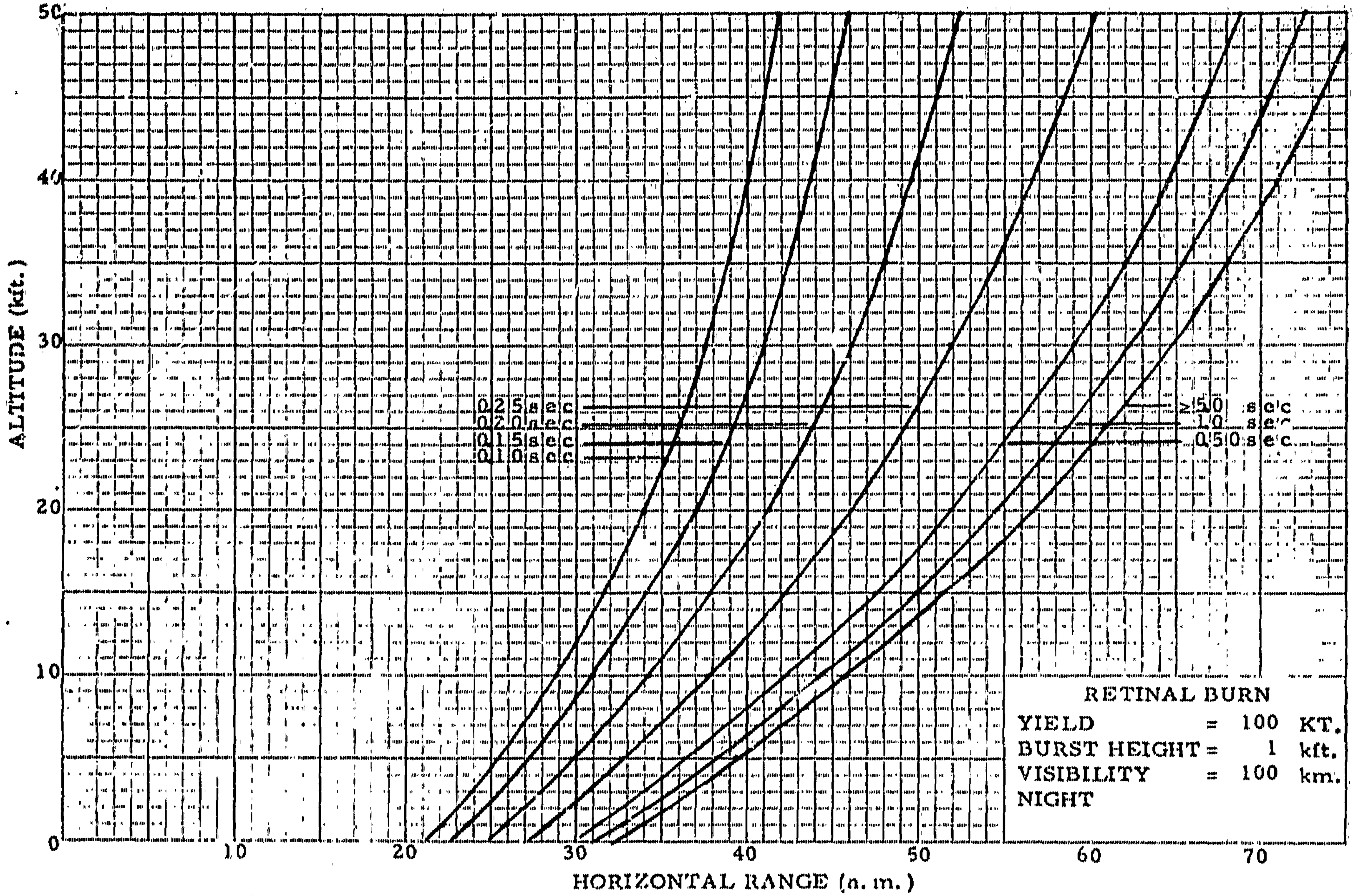


50
40
30
20
10
0
ALTITUDE (kft.)
10
20
30
40
50
60
70
HORIZONTAL RANGE (n. m.)
0.25 sec
0.20 sec
0.15 sec
0.10 sec
≥5.0 sec
1.0 sec
0.50 sec
RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
NIGHT

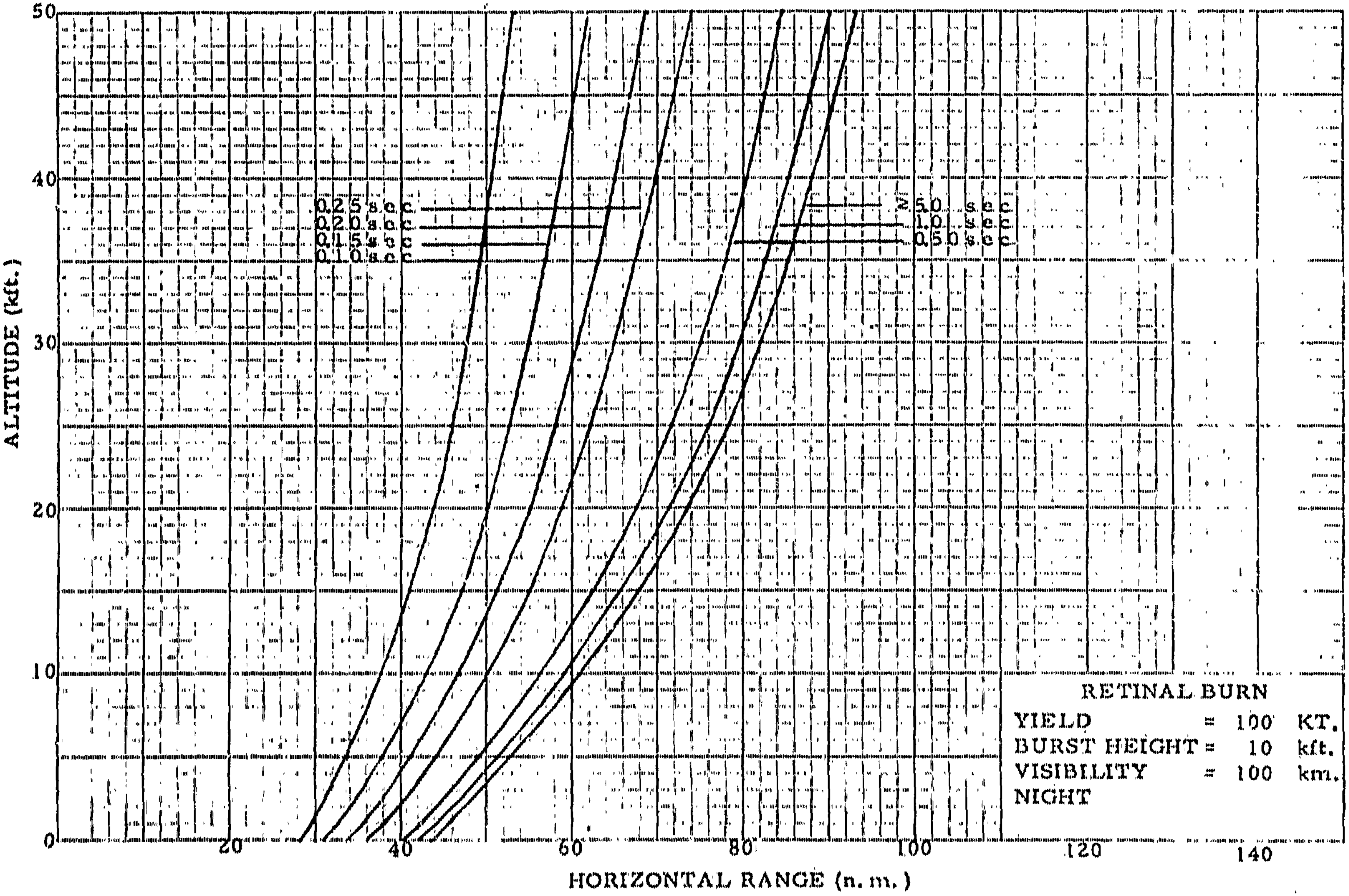

0.25 sec
0.20 sec
0.15 sec
0.10 sec
≥5.0 sec
1.0 sec
0.50 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
20
40
60
80
100
120
140
RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
NIGHT

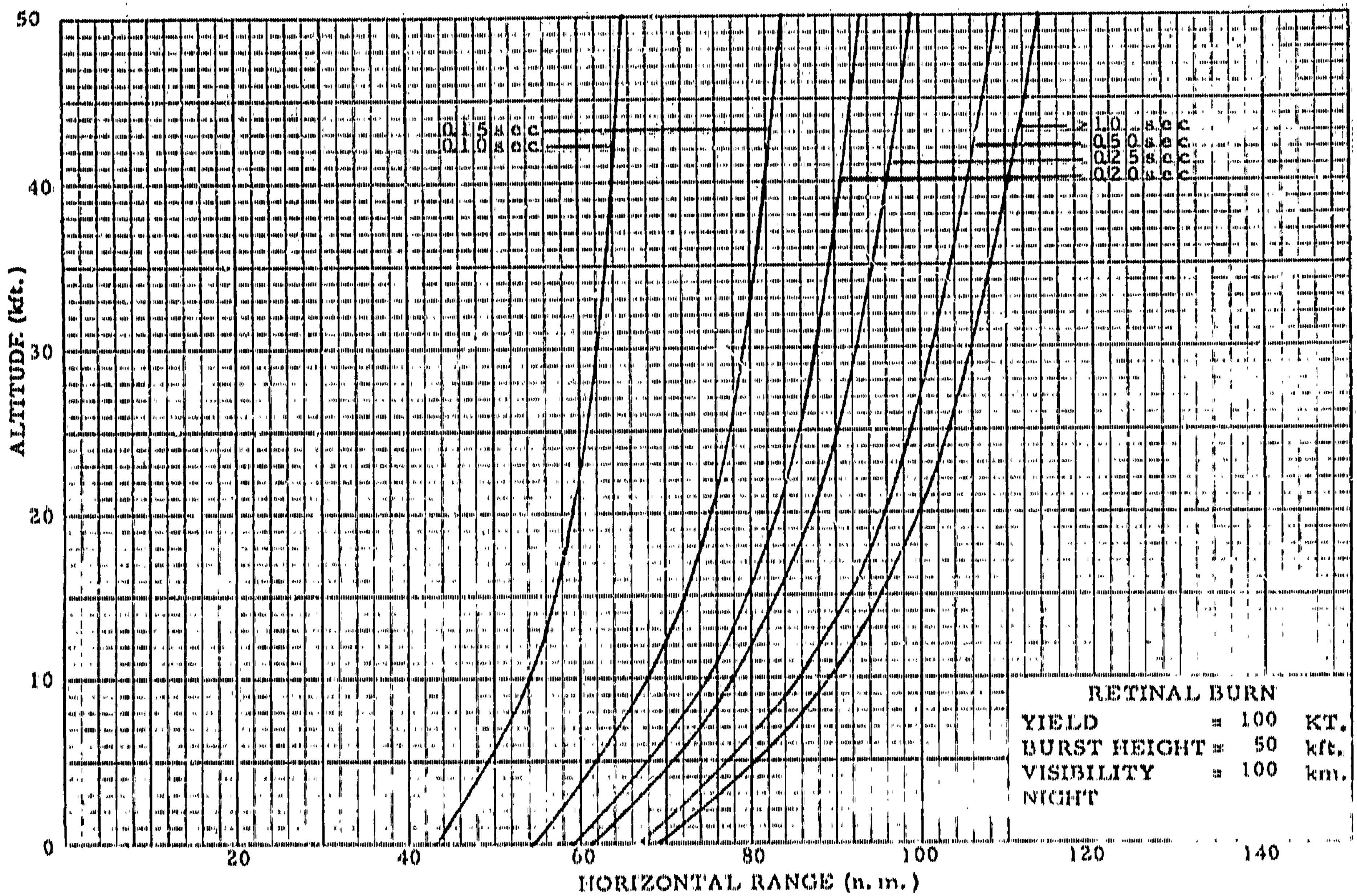


RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
NIGHT
≥1.0 sec
0.50 sec
0.25 sec
0.20 sec
0.15 sec
0.10 sec
ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n. m.)
20
40
60
80
100
120
140

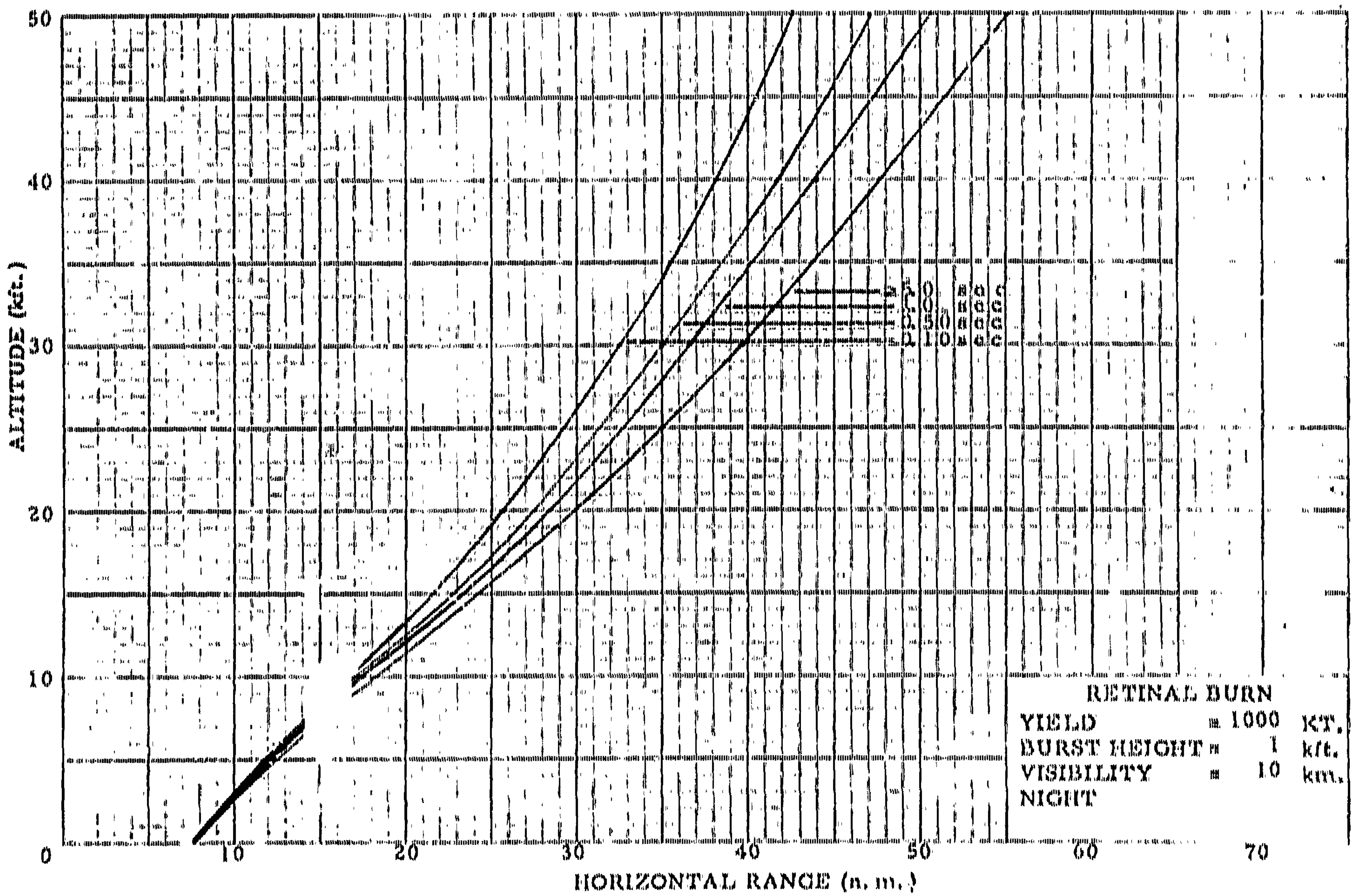


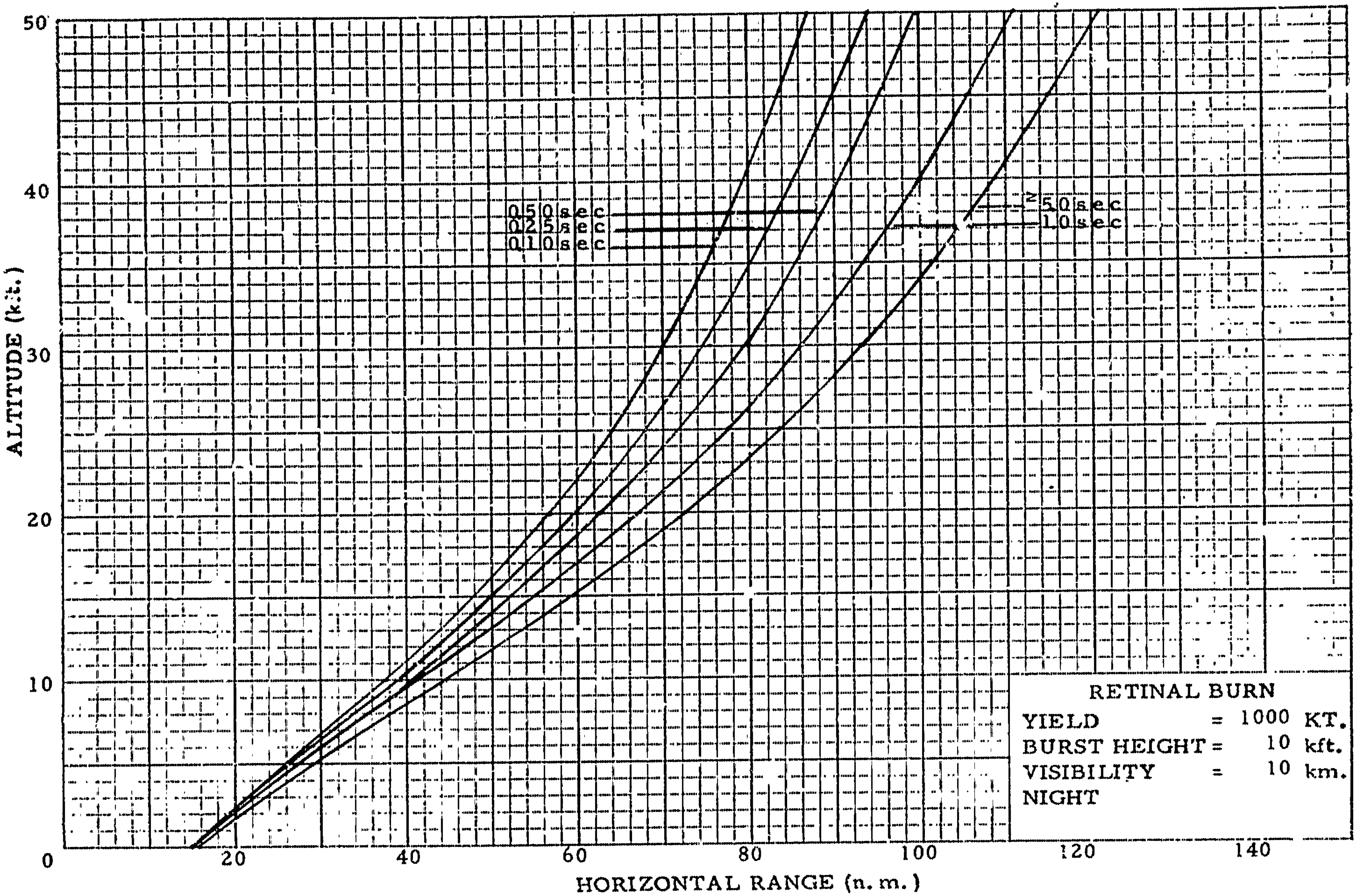
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0.25 sec
0.20 sec
0.15 sec
0.10 sec
≥5.0 sec
1.0 sec
0.50 sec
RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT

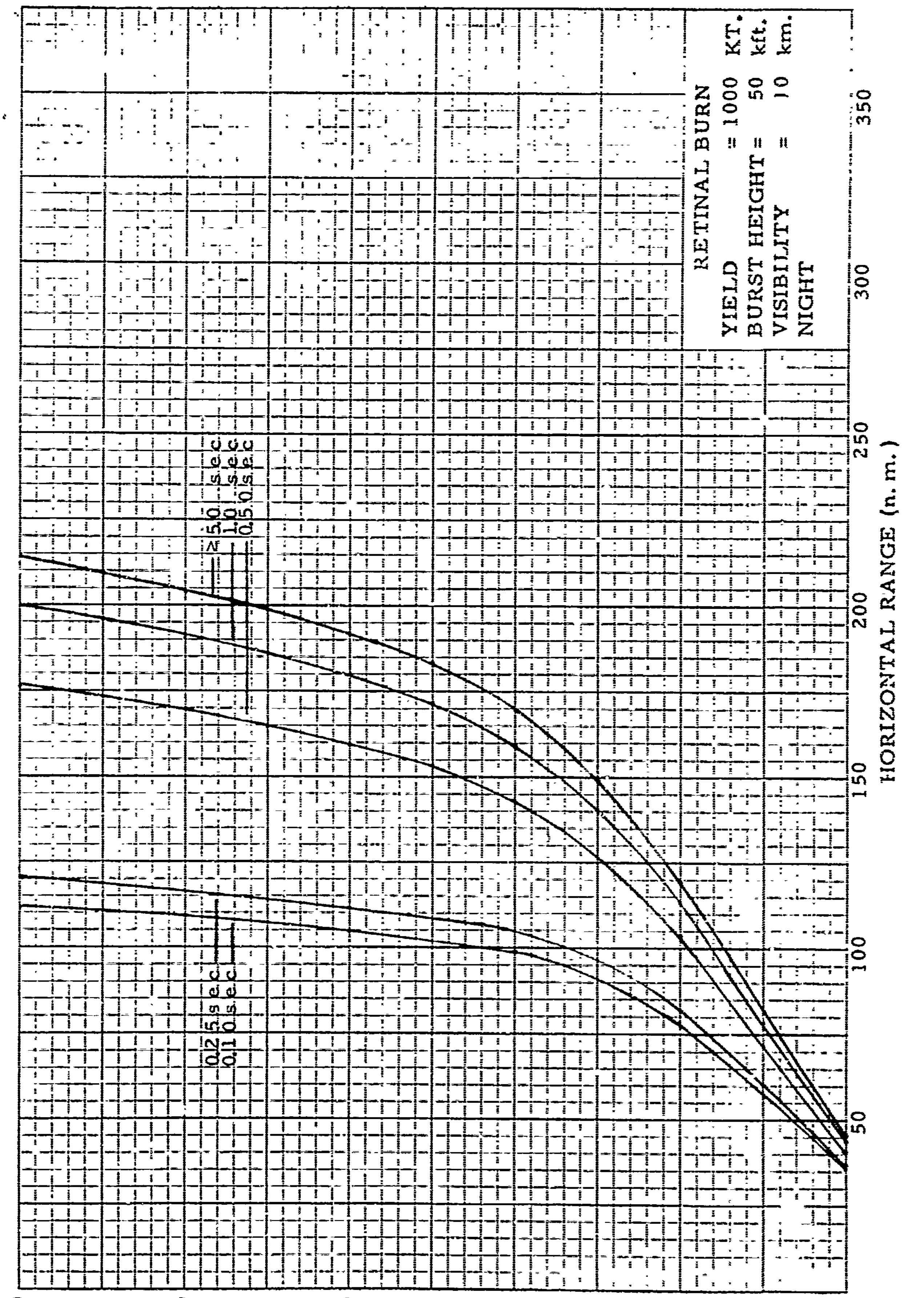

RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT
0.25 sec
0.20 sec
0.15 sec
0.10 sec
≥5.0 sec
1.0 sec
0.50 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
20
40
60
80
100
120
140

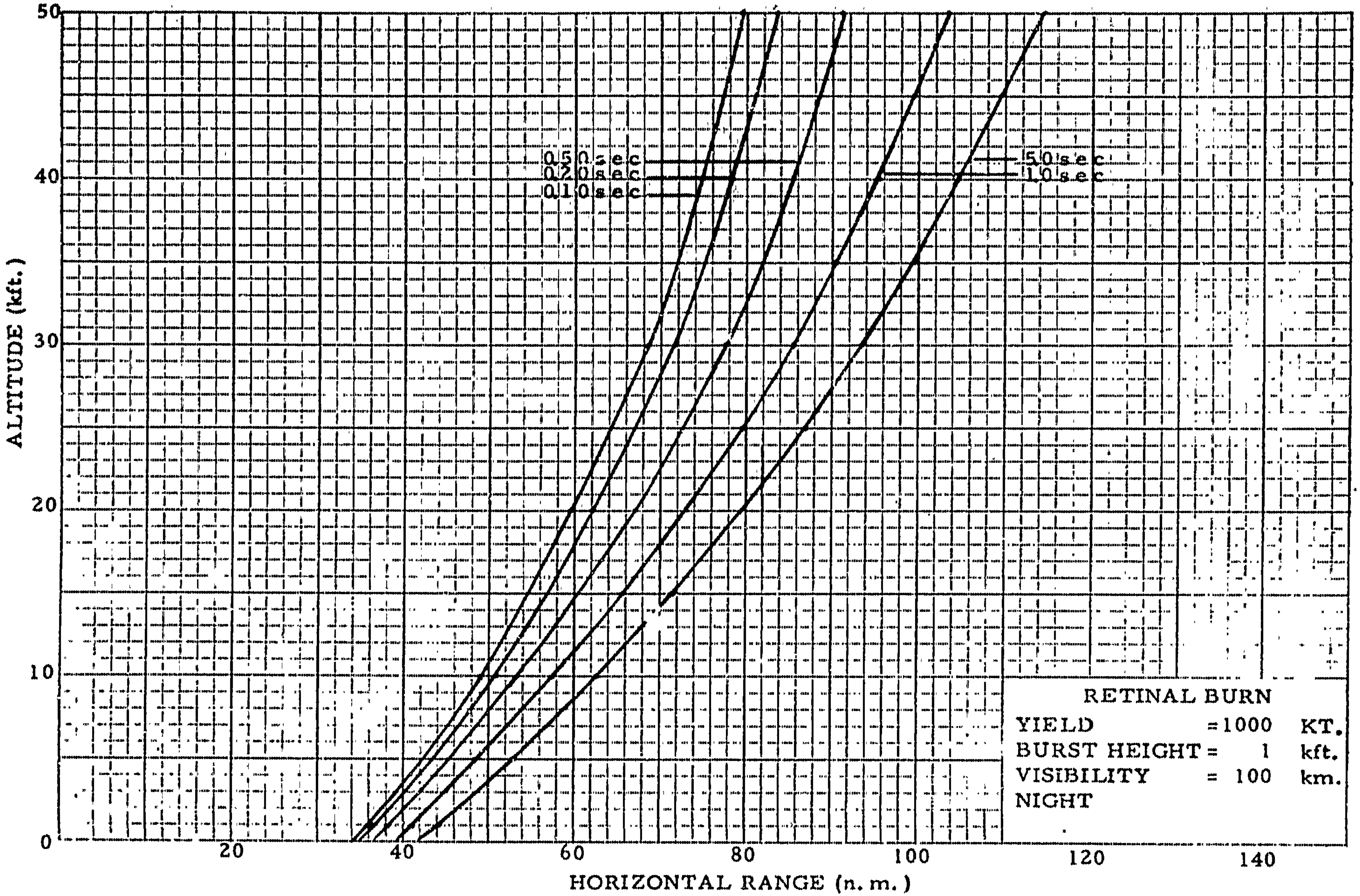


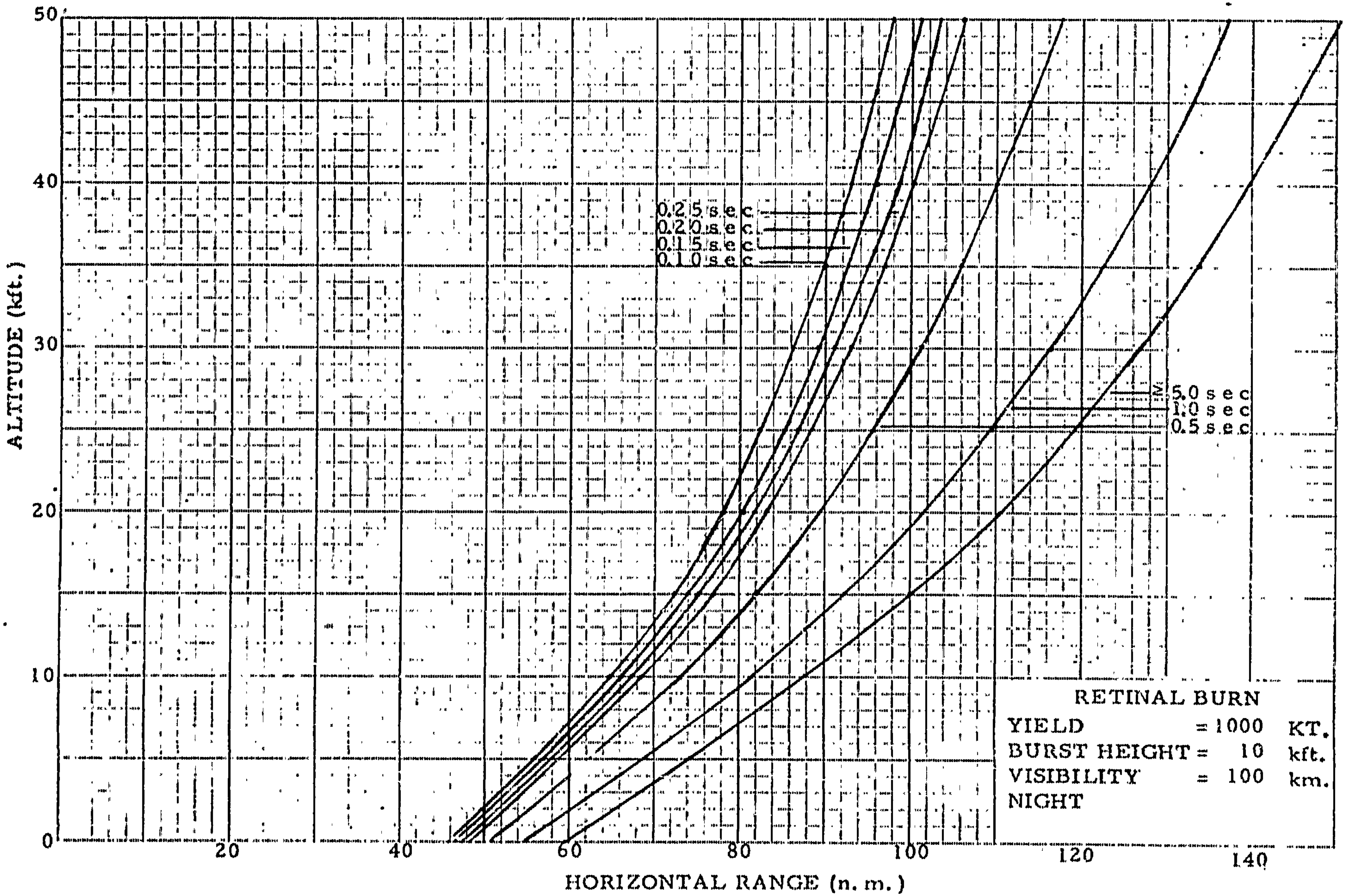
0.15 sec
0.10 sec
≥1.0 sec
0.50 sec
0.25 sec
0.20 sec
RETINAL BURN
YIELD = 100 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)

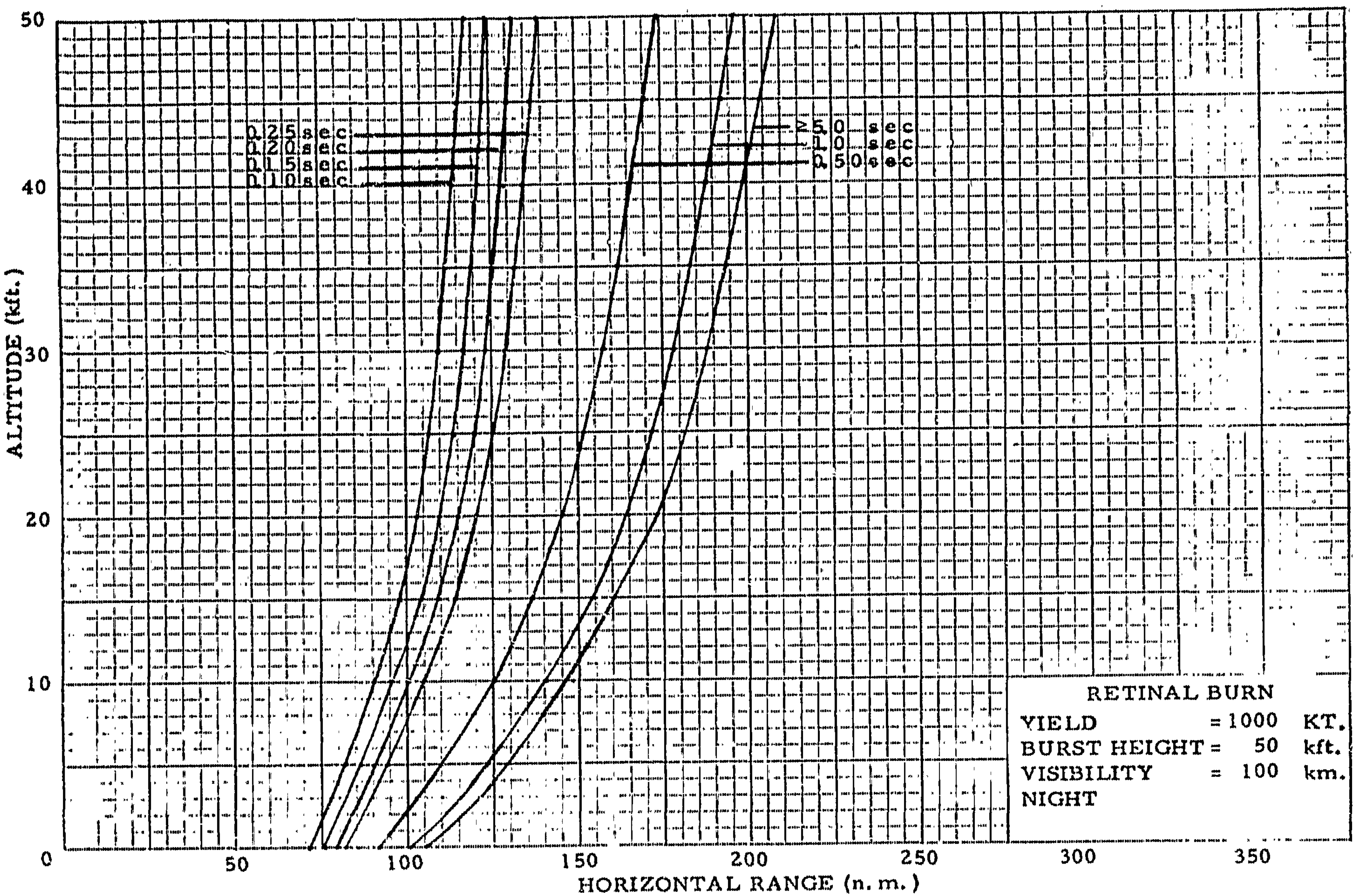

ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70
RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
NIGHT

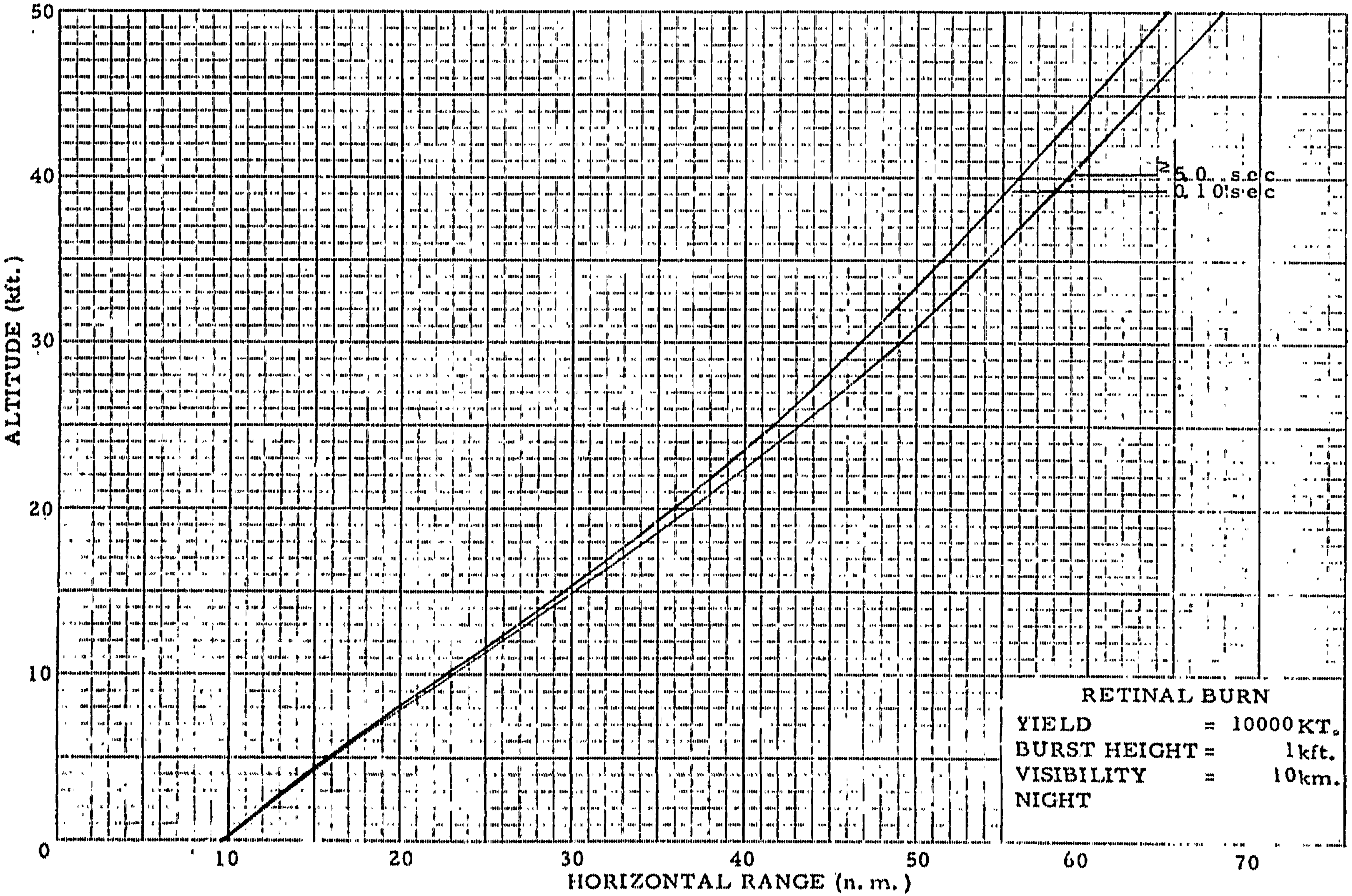

0.50 sec
0.25 sec
0.10 sec
≥5.0 sec
1.0 sec
RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
NIGHT
ALTITUDE (k.ft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
20
40
60
80
100
120
140


RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
NIGHT
≥5.0 sec
1.0 sec
0.5 0 sec
0.25 sec
0.1 0 sec
HORIZONTAL RANGE (n. m.)
0
50
100
150
200
250
300
350
ALTITUDE (kft.)
0
10
20
30
40
50

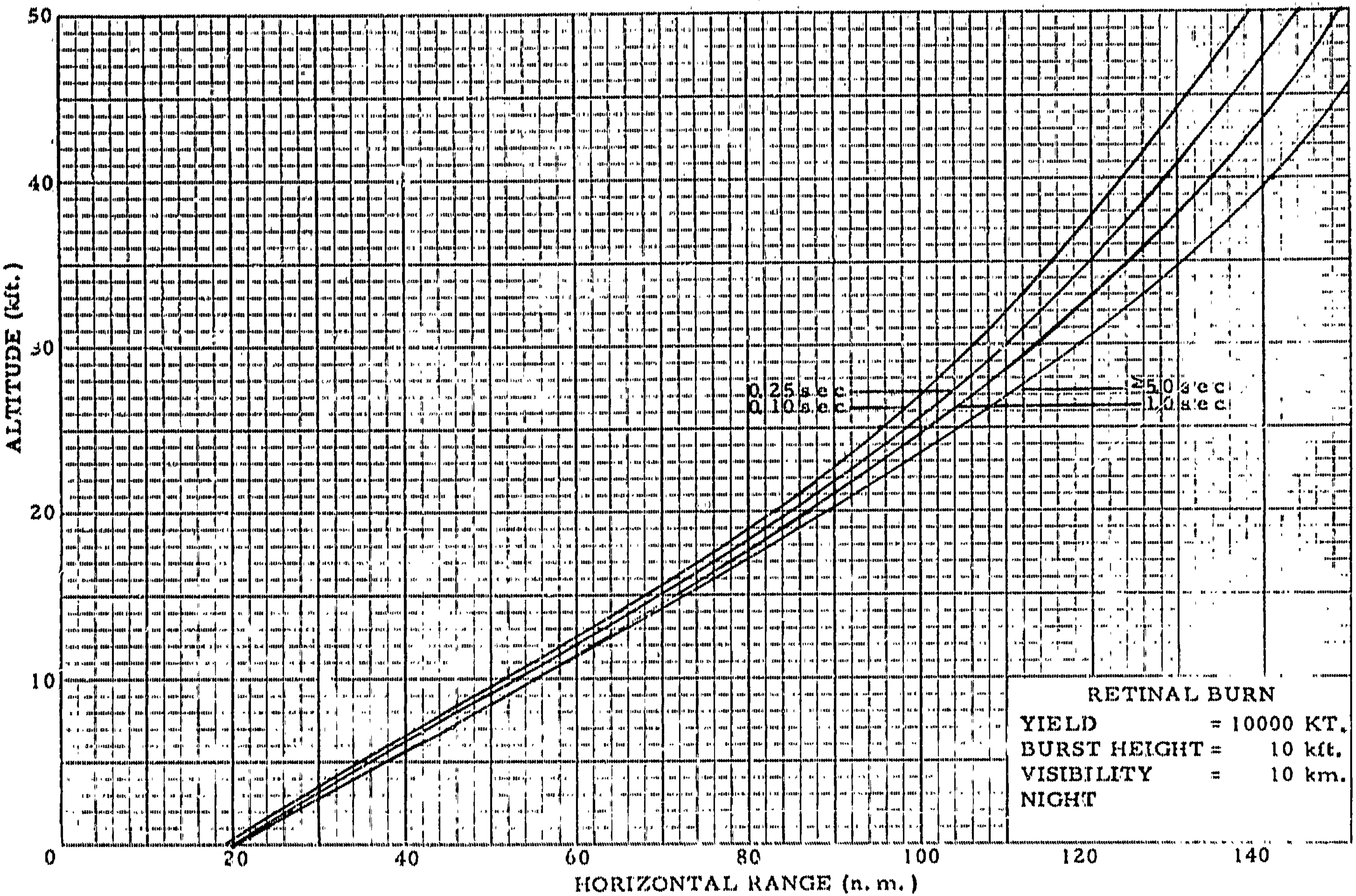

RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT
0.50 sec
0.20 sec
0.10 sec
5.0 sec
1.0 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
20
40
60
80
100
120
140


RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT
0.25 sec
0.20 sec
0.15 sec
0.10 sec
≥5.0 sec
1.0 sec
0.5 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
80
100
120
140

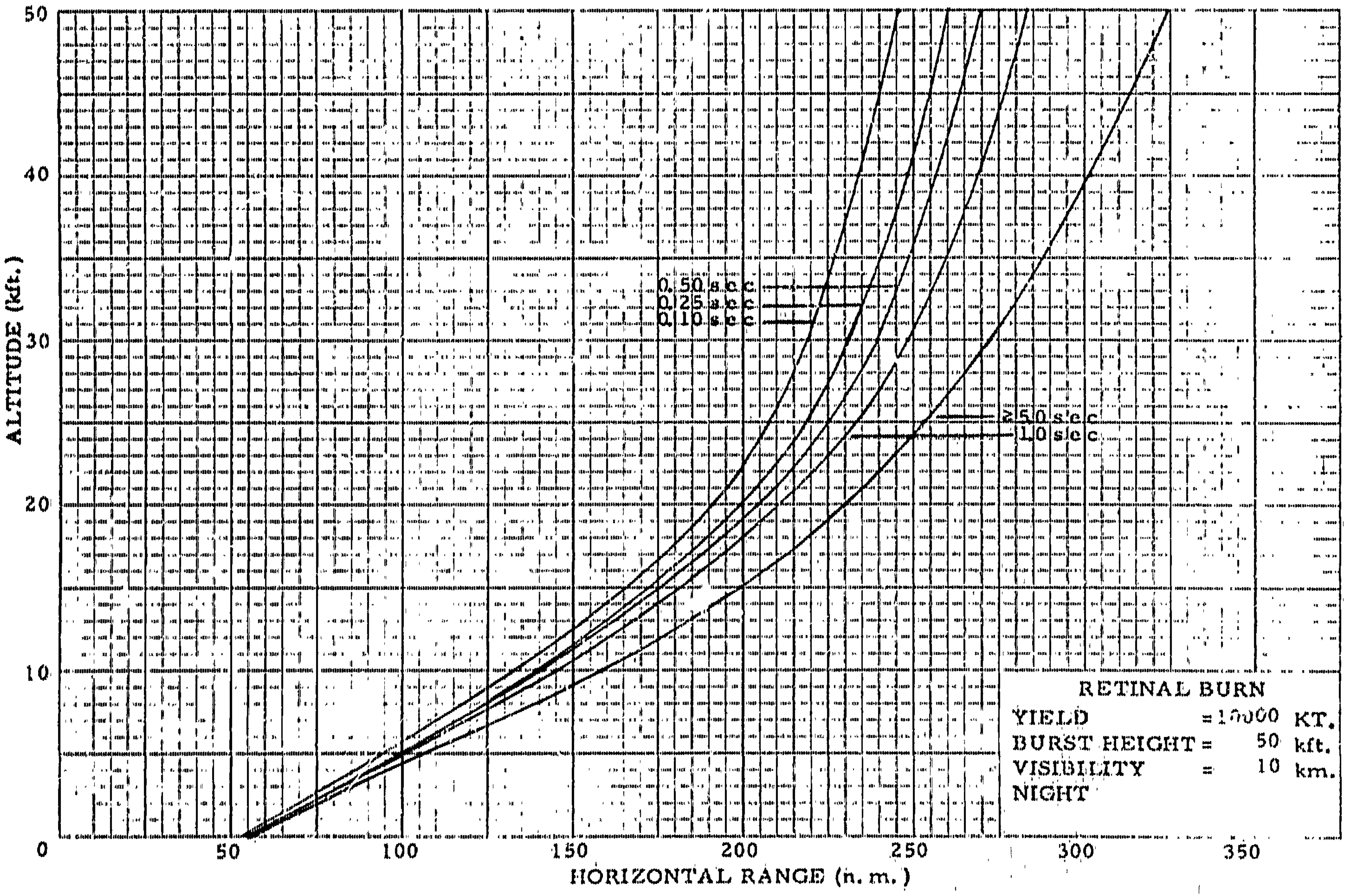

0.25 sec
0.20 sec
0.15 sec
0.10 sec
≥5.0 sec
1.0 sec
0.50 sec
RETINAL BURN
YIELD = 1000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
50
100
150
200
250
300
350



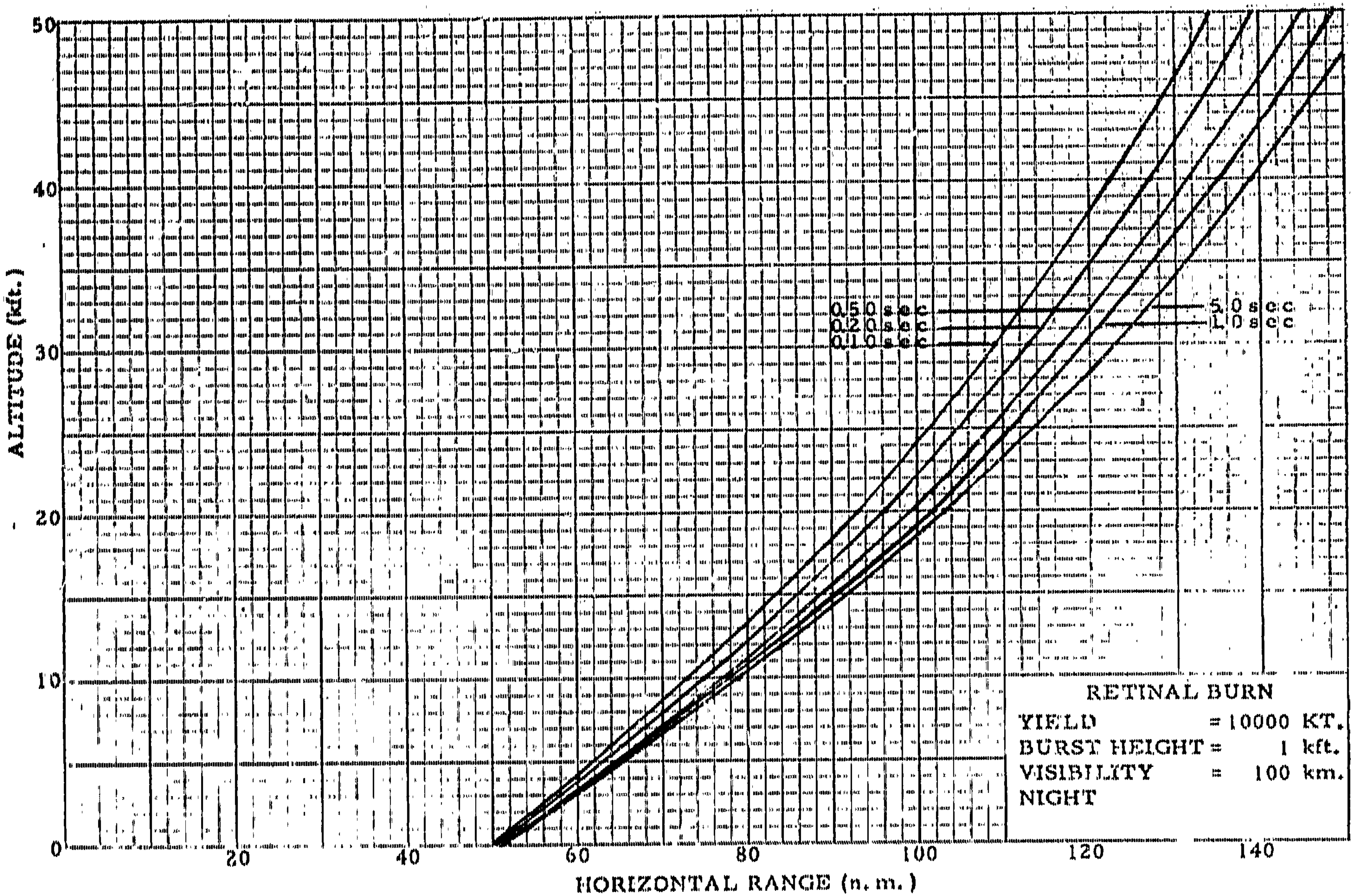
RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 10 km.
NIGHT
≥ 5.0 sec
0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70



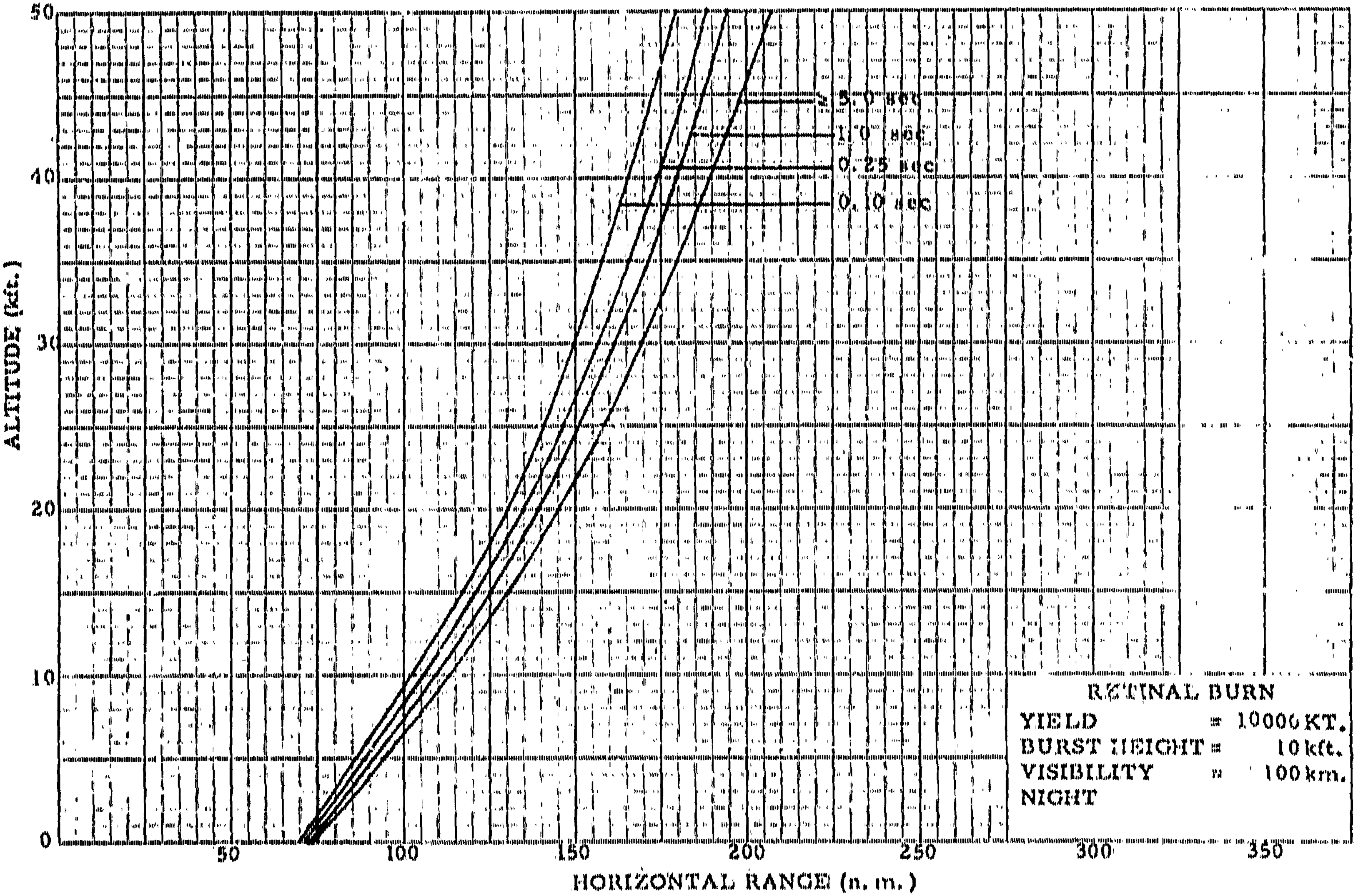
50
40
30
20
10
0
ALTITUDE (kft.)
20
40
60
80
100
120
140
HORIZONTAL RANGE (n. m.)
0.25 sec
0.10 sec
≥5.0 sec
1.0 sec
RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 10 km.
NIGHT

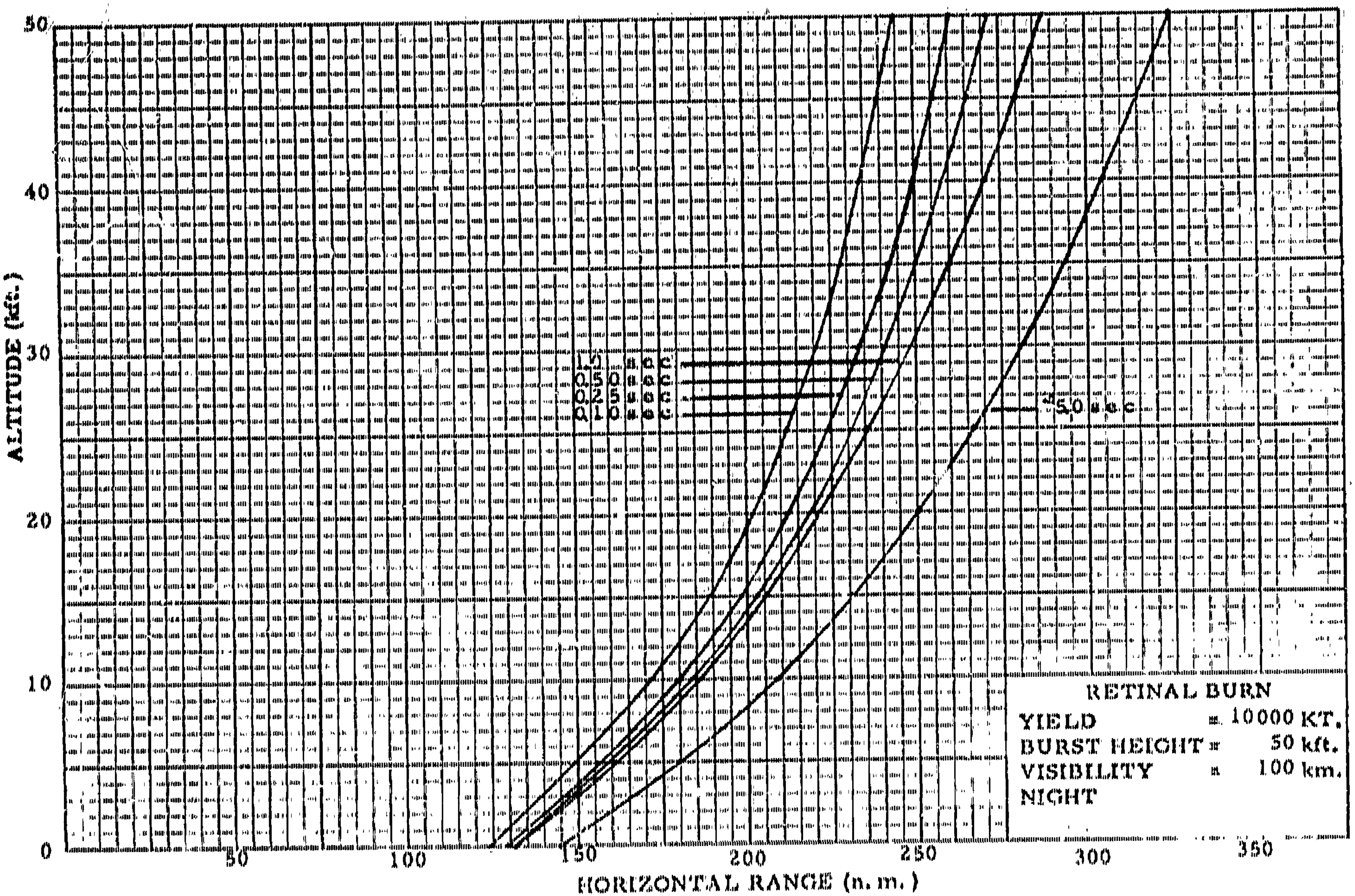


0.50 sec
0.25 sec
0.10 sec
≥ 5.0 sec
1.0 sec
RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 10 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
100
150
200
250
300
350



RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT
0.50 sec
0.20 sec
0.10 sec
5.0 sec
1.0 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
20
40
60
80
100
120
140


RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT
5.0 sec
1.0 sec
0.25 sec
0.10 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
100
150
200
250
300
350


ALTITUDE (kft.)
0
10
20
30
40
50
HORIZONTAL RANGE (n. m.)
50
100
150
200
250
300
350
1.0 sec
0.50 sec
0.25 sec
0.10 sec
5.0 sec
RETINAL BURN
YIELD = 10000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT

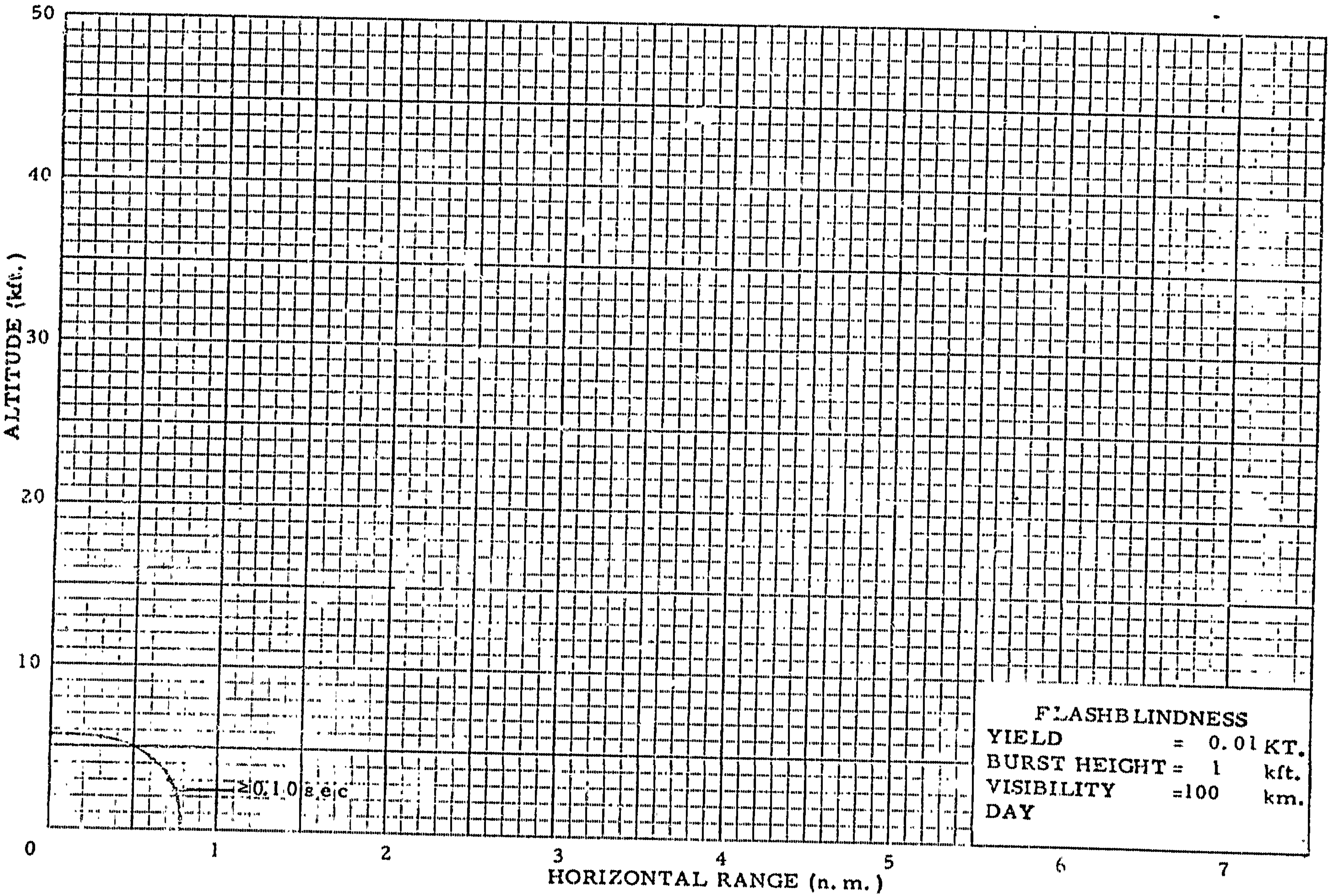
APPENDIX B

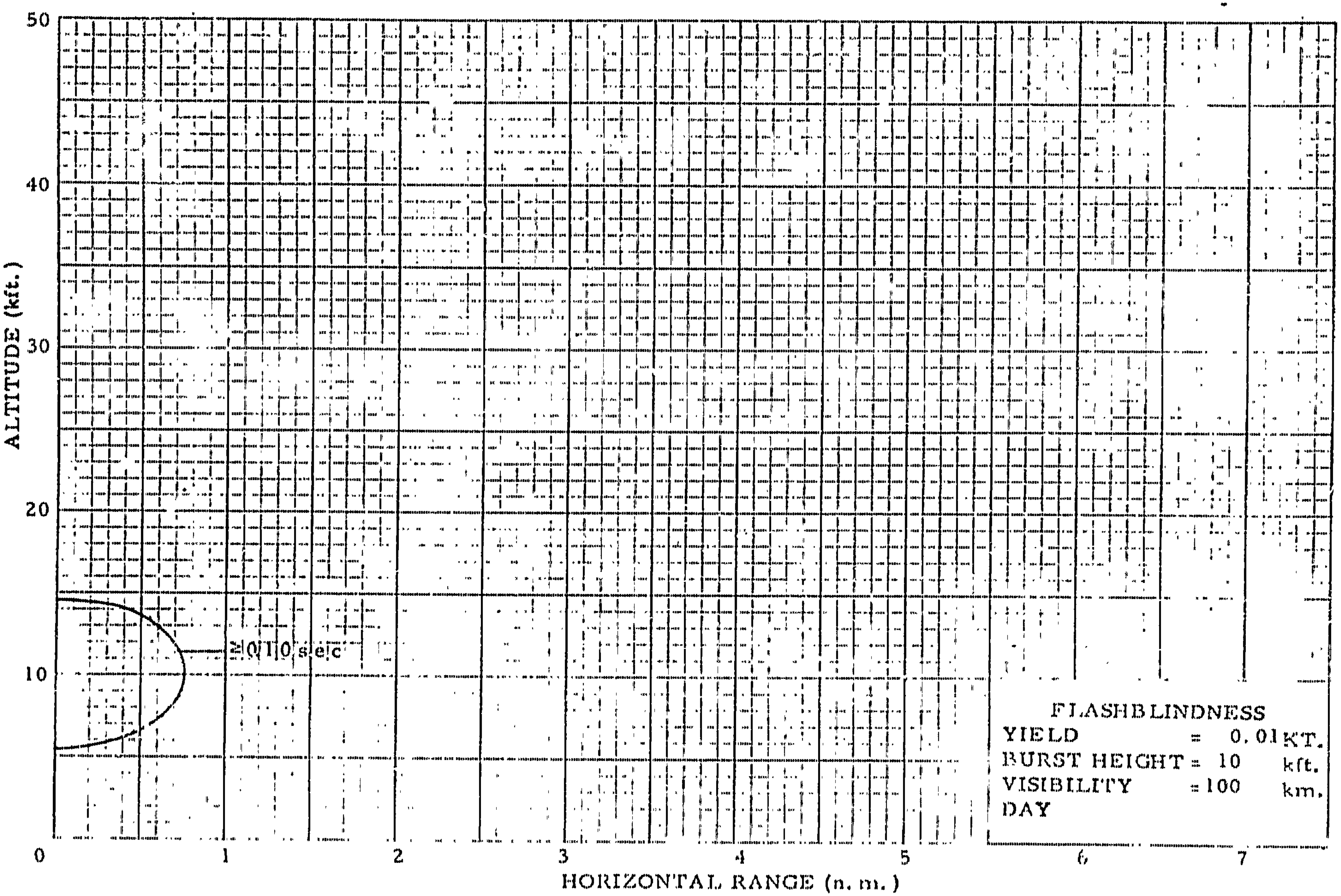
FLASHBLINDNESS SAFE SEPARATION DISTANCE CURVES

FLASHBLINDNESS SAFE SEPARATION DISTANCE CURVES

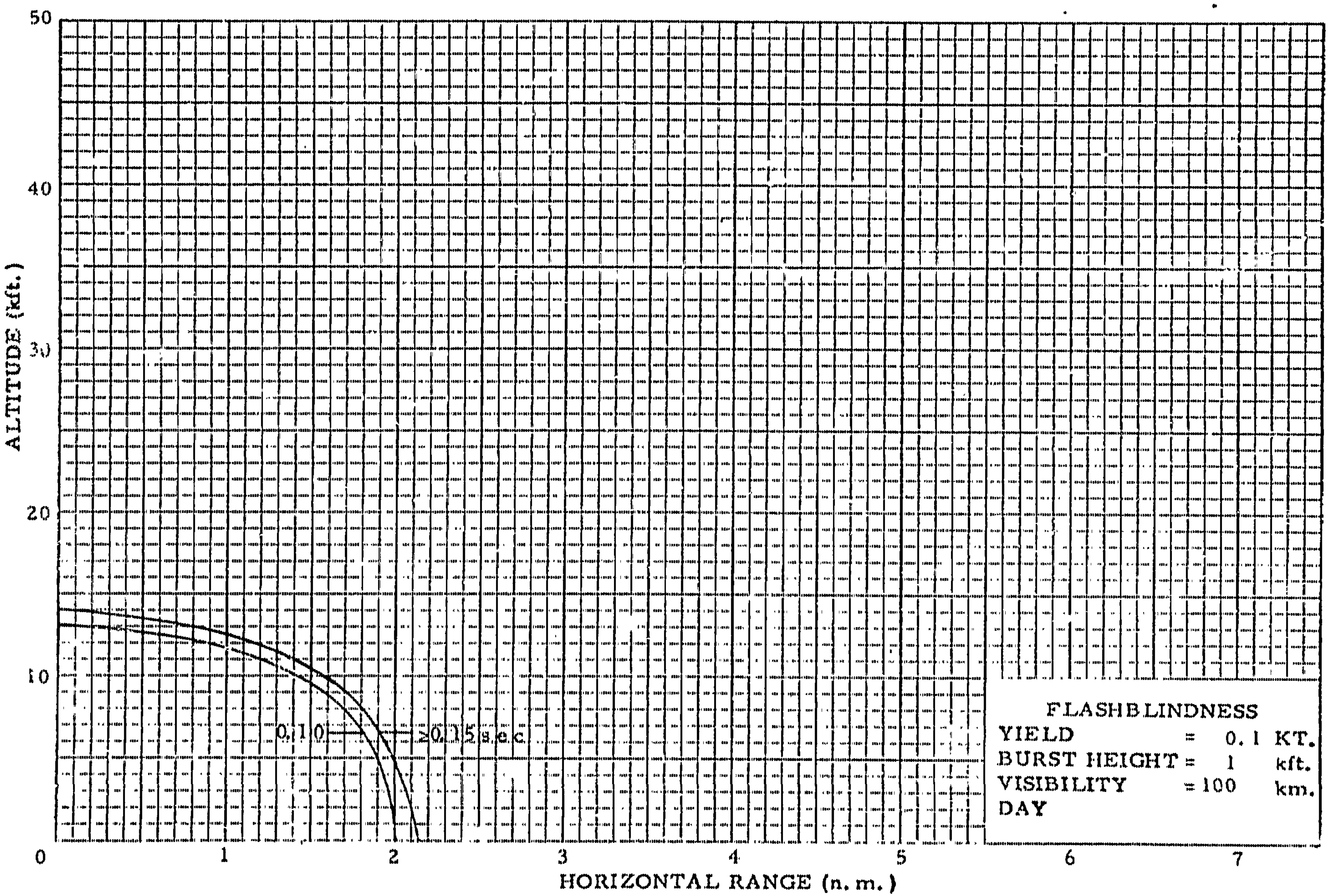
Safe separation distances for flashblindness have been determined as explained in this report for seven yields (.01, .10, 1.0, 10., 100., 1000., and 10000. KT), three burst heights (1.0, 10.0, and 50. kft.), one visibility (100 km.), and for day and night conditions. The results are presented in this appendix as a set of graphs of safe separation distance versus observer altitude. Each graph is plotted for a specified yield, burst height, and for day or night conditions, with blink time as the parameter between curves. Seven blink times (.10, .15, .20, .25, .50, 1.0, and 5.0 sec) are included on each graph except where the interpolation from one blink time to another is evident.

The graphs for day conditions are presented first and followed by those for night conditions. Each of these major divisions is then subdivided by the yields in ascending order, and a further subdivision is made for the increasing burst heights. The safe separation distances obtained from these graphs for weapons detonated at 50 kft. should be used with prudence.

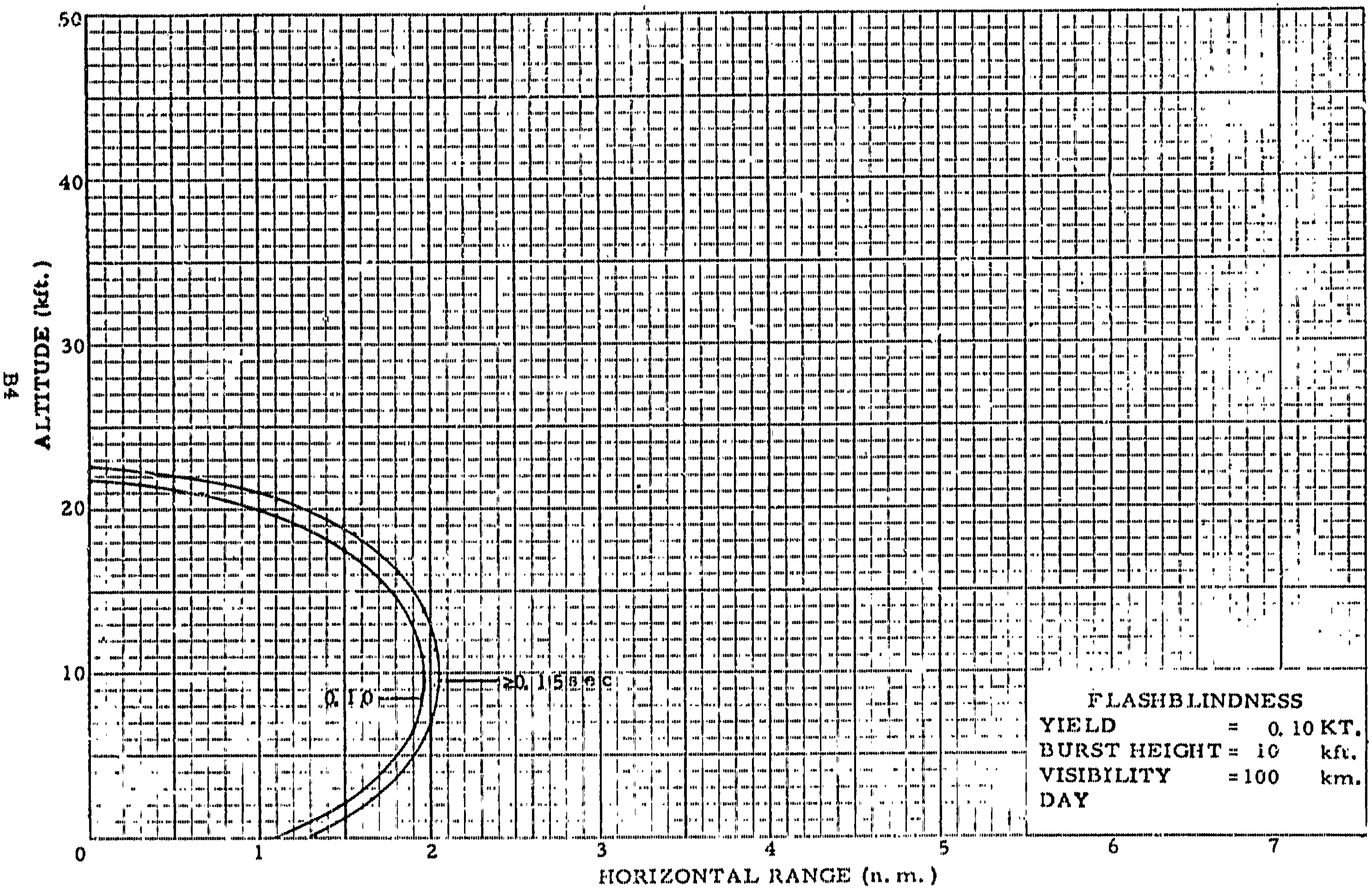

ALTITUDE (kft.)
50
40
30
20
10
0
1
2
3
4
5
6
7
HORIZONTAL RANGE (n. m.)
≥0.1.0 sec
FLASHBLINDNESS
YIELD = 0.01 KT.
BURST HEIGHT = 1 kft.
VISIBILITY =100 km.
DAY


50
40
30
20
10
0
ALTITUDE (kft.)
1
2
3
4
5
6
7
HORIZONTAL RANGE (n. m.)
≥0.10 sec
FLASHBLINDNESS
YIELD = 0.01 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY

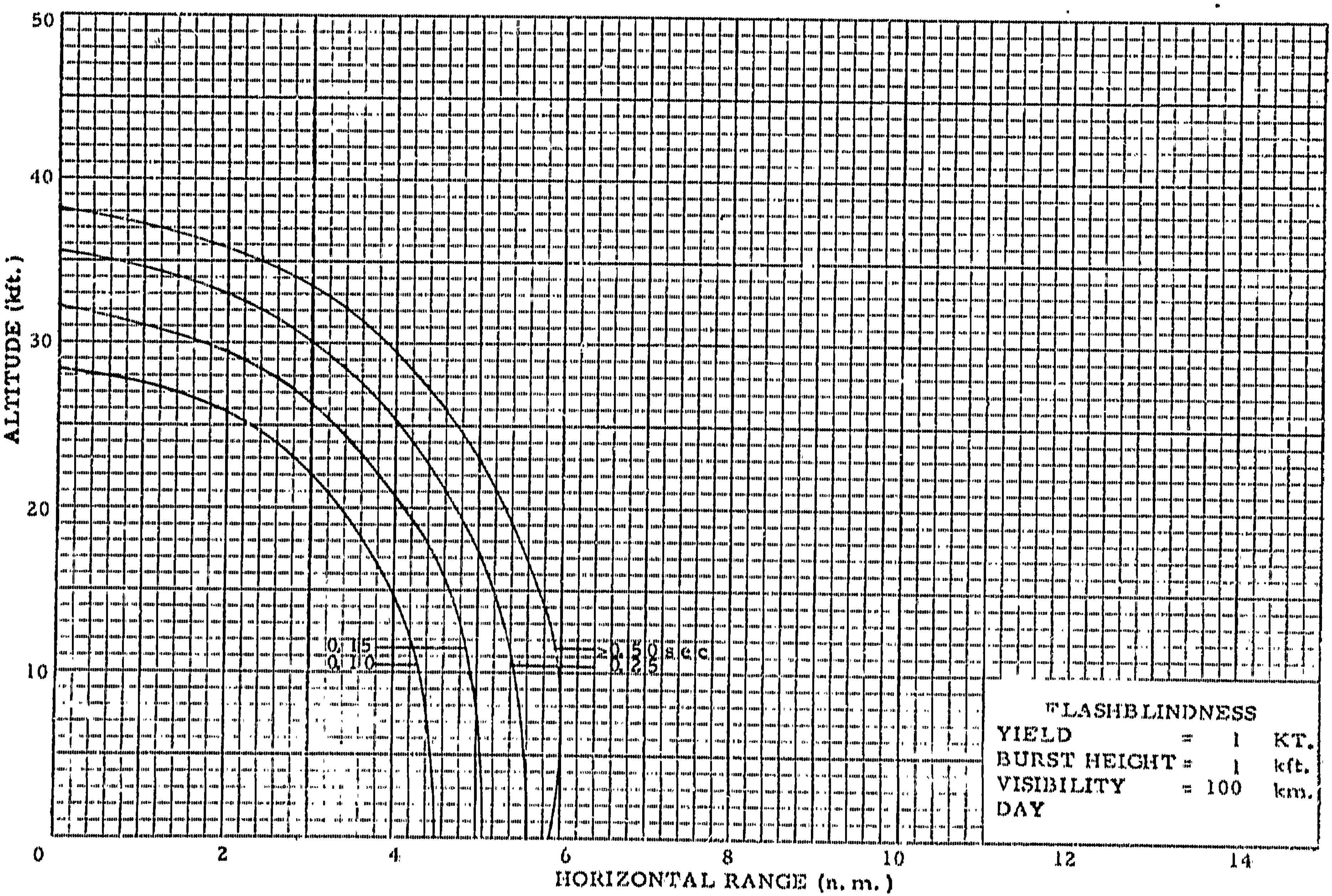
B2

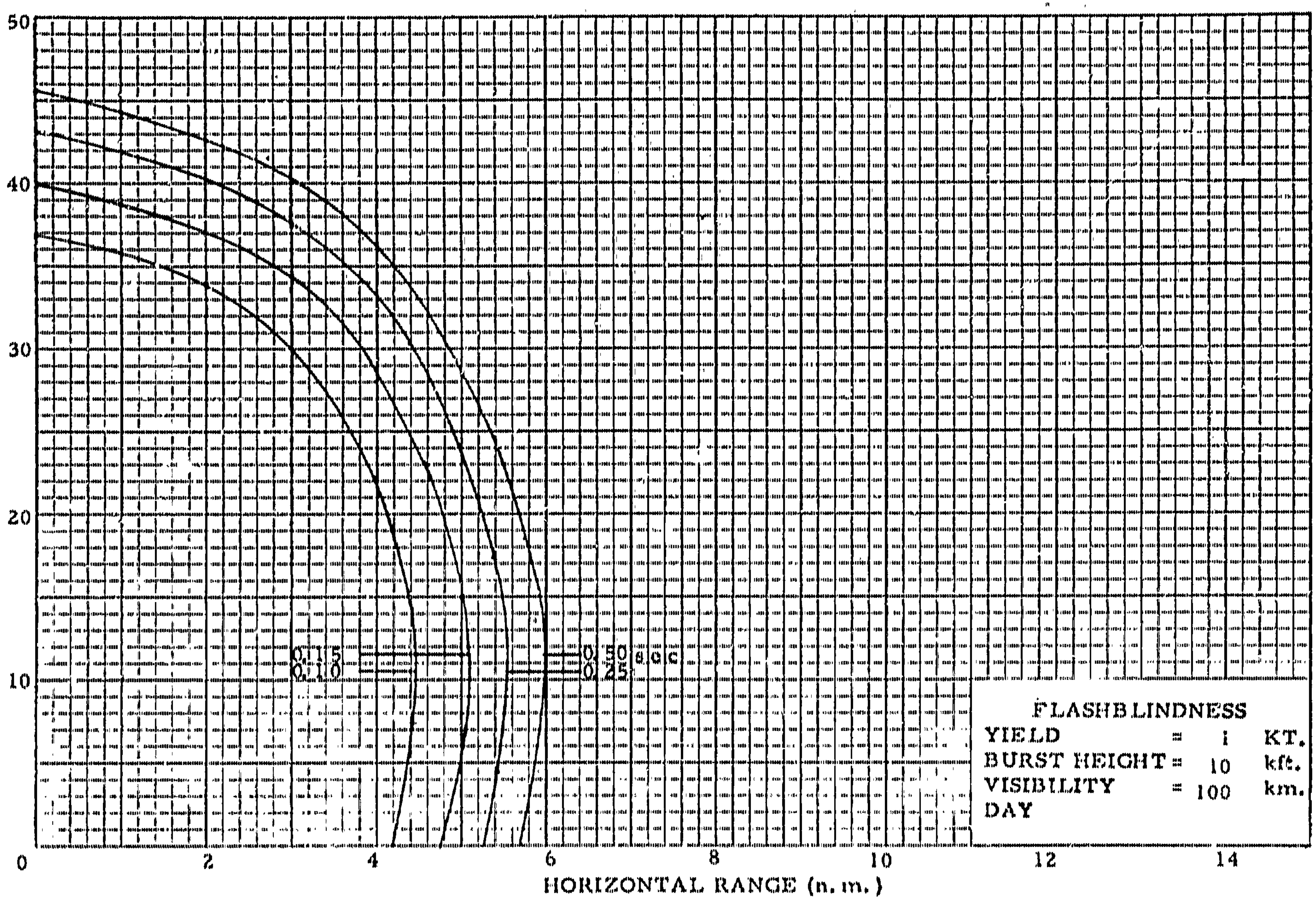


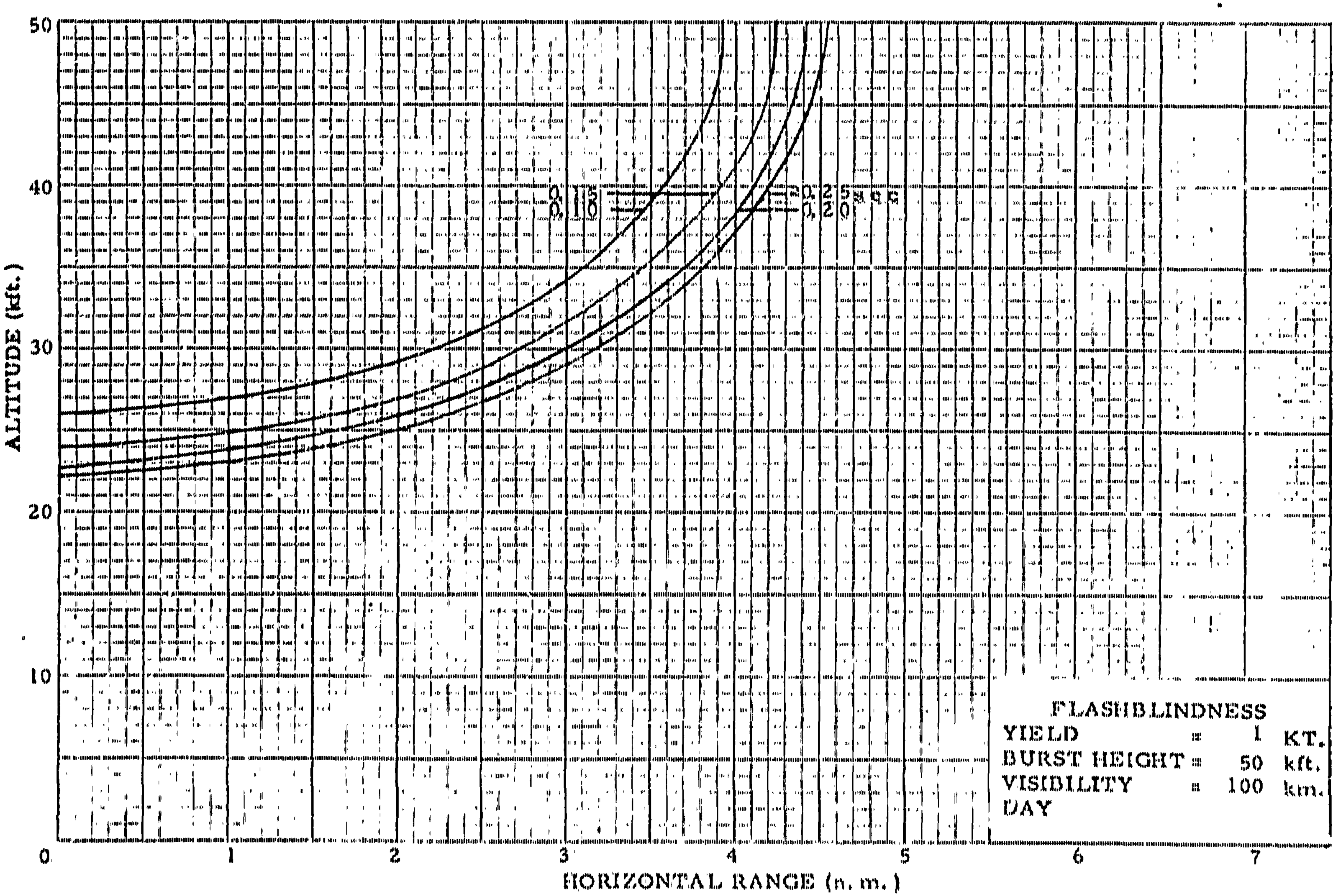
FLASHBLINDNESS
YIELD = 0.1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY
0.10
0.15 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
1
2
3
4
5
6
7

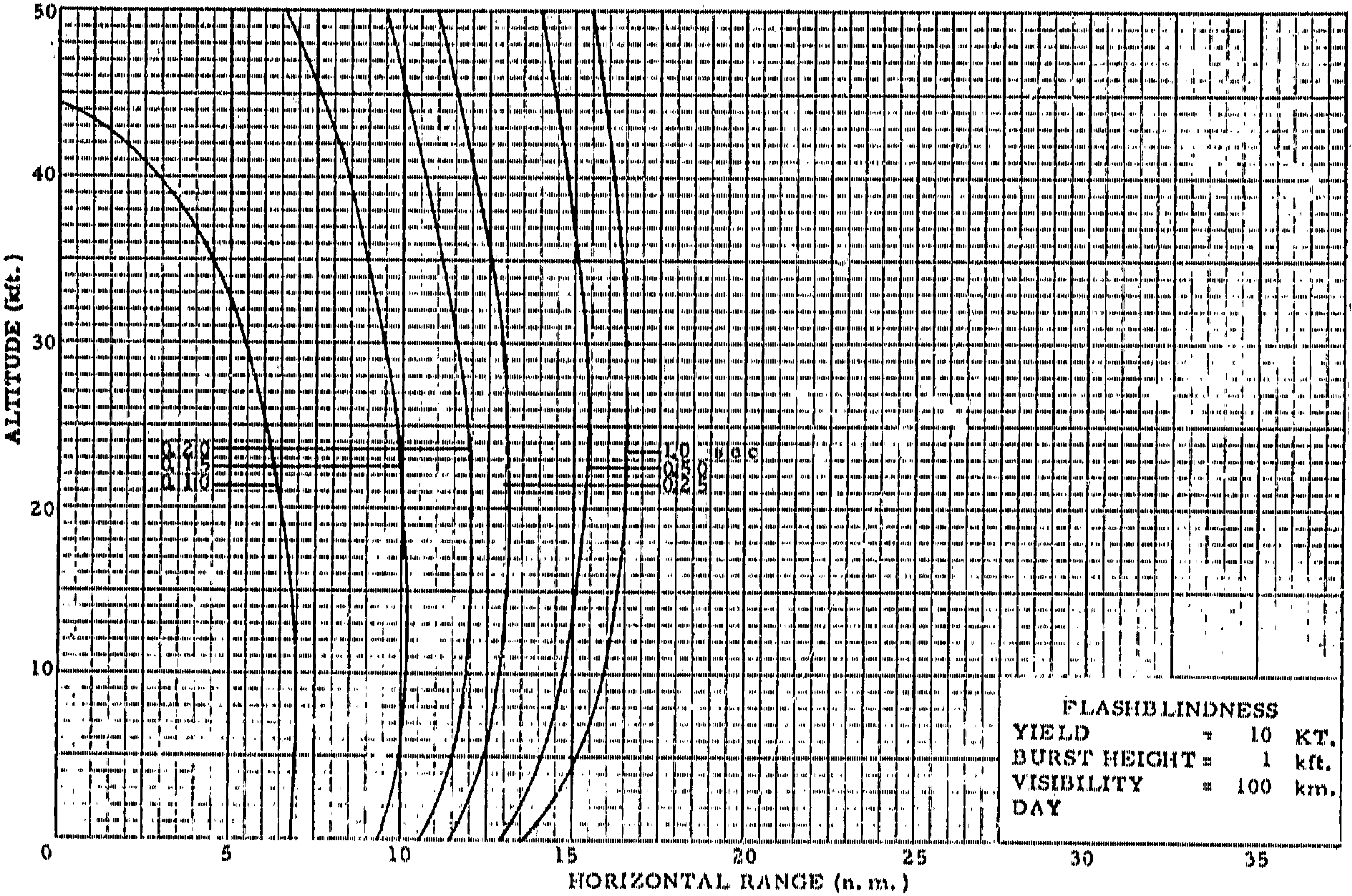


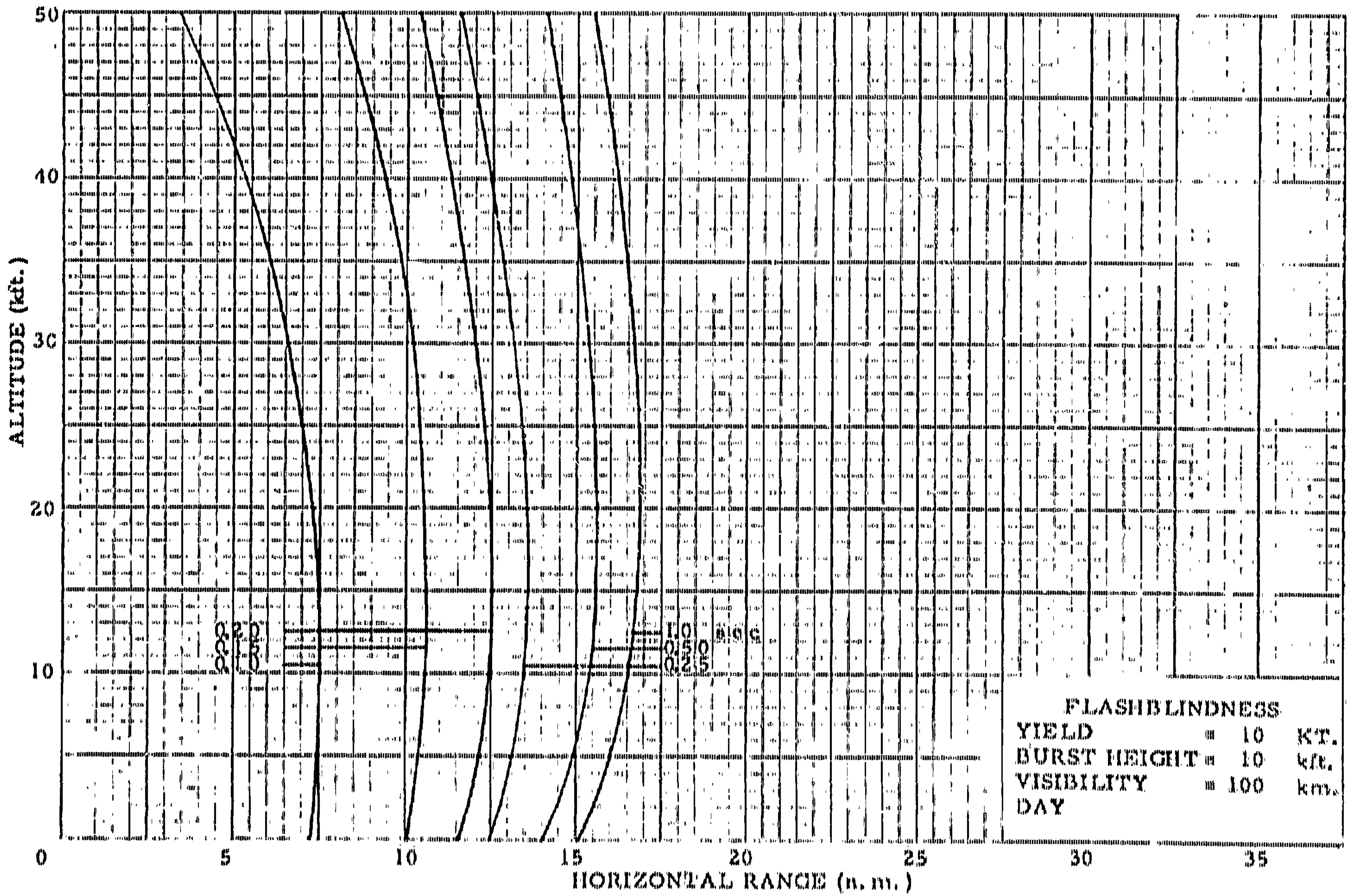
ALTITUDE (kft.)
50
40
30
20
10
0
1
2
3
4
5
6
7
HORIZONTAL RANGE (n. m.)
0.10
≥0.15 sec
FLASHBLINDNESS
YIELD = 0.10 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY

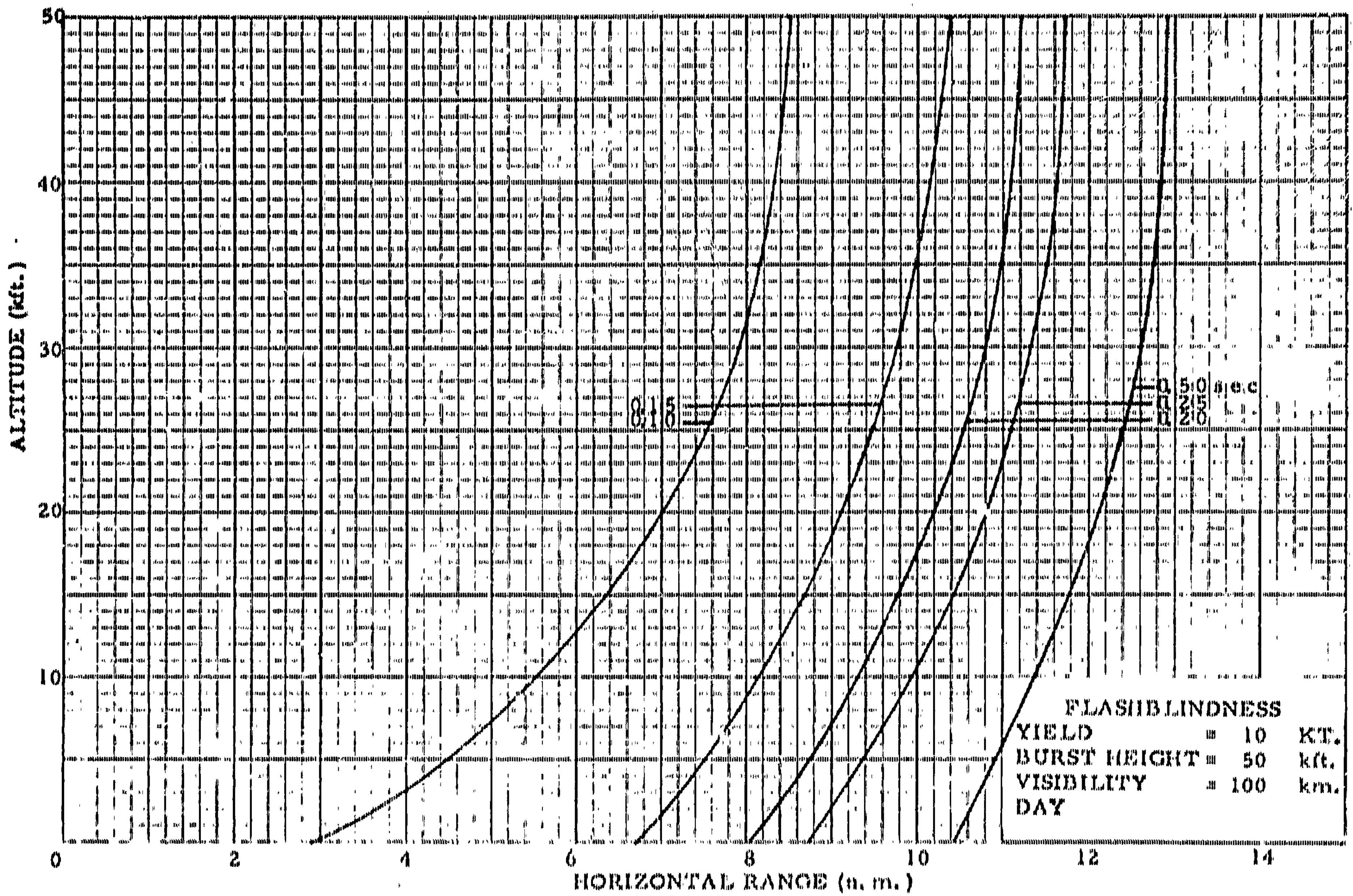

FLASHBLINDNESS
YIELD = 1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY
0.15
0.10
0.50 sec
0.25
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
2
4
6
8
10
12
14
10
20
30
40
50


ALTITUDE (kft.)
50
40
30
20
10
0
2
4
6
8
10
12
14
HORIZONTAL RANGE (n.m.)
0.115
0.10
0.50 sec
0.25
FLASHBLINDNESS
YIELD = 1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY

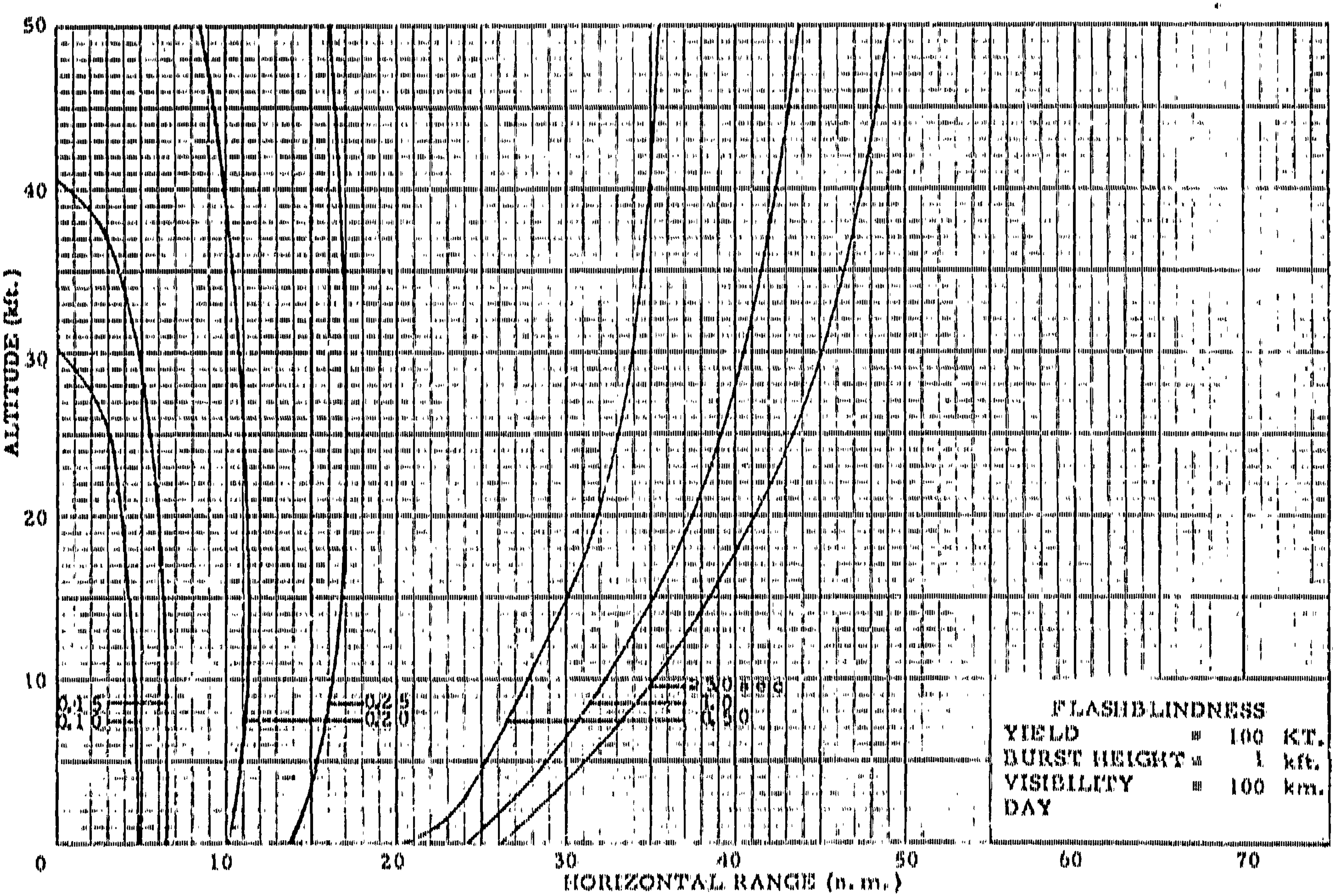

ALTITUDE (kft.)
50
40
30
20
10
0
1
2
3
4
5
6
7
HORIZONTAL RANGE (n. m.)
0.15
0.10
0.25
0.20
FLASHBLINDNESS
YIELD = 1 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY

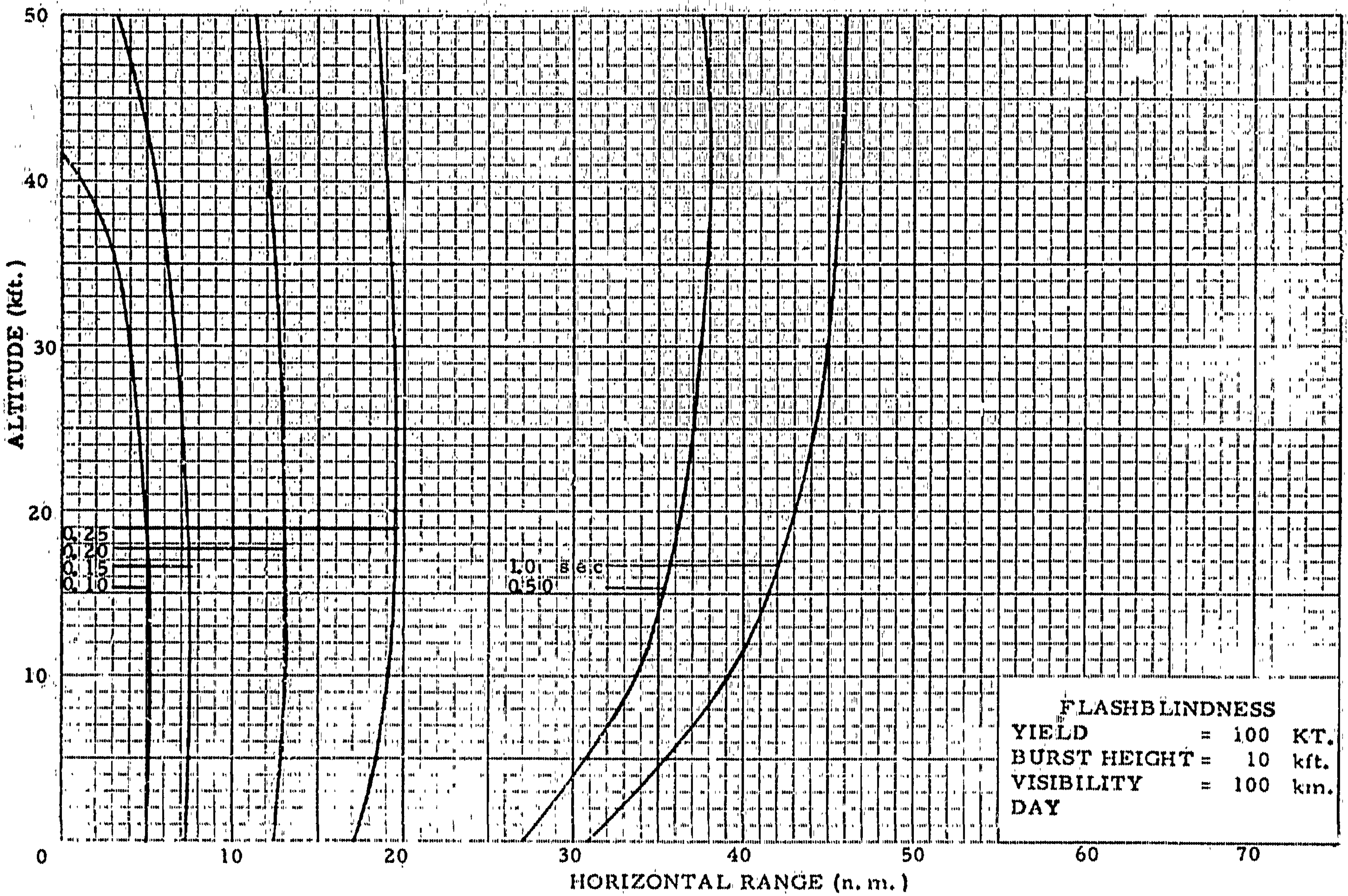

FLASHBLINDNESS
YIELD = 10 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY
0.120
0.115
0.110
1.0 sec
0.50
0.25
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
5
10
15
20
25
30
35
10
20
30
40
50

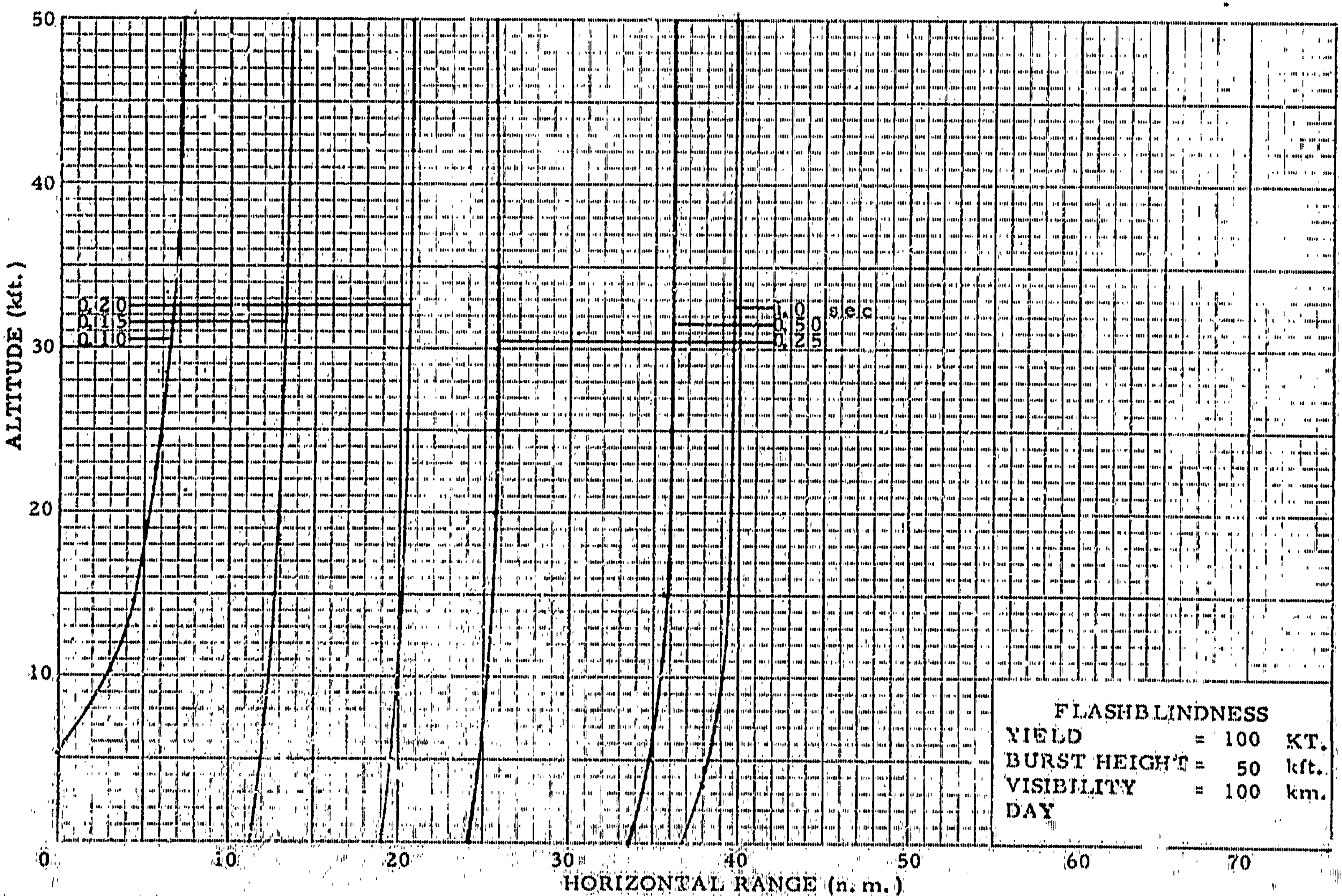

ALTITUDE (kft.)
50
40
30
20
10
0
5
10
15
20
25
30
35
HORIZONTAL RANGE (n. mi.)
0.20
0.15
0.10
1.0 sec
0.50
0.25
FLASHBLINDNESS
YIELD = 10 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY



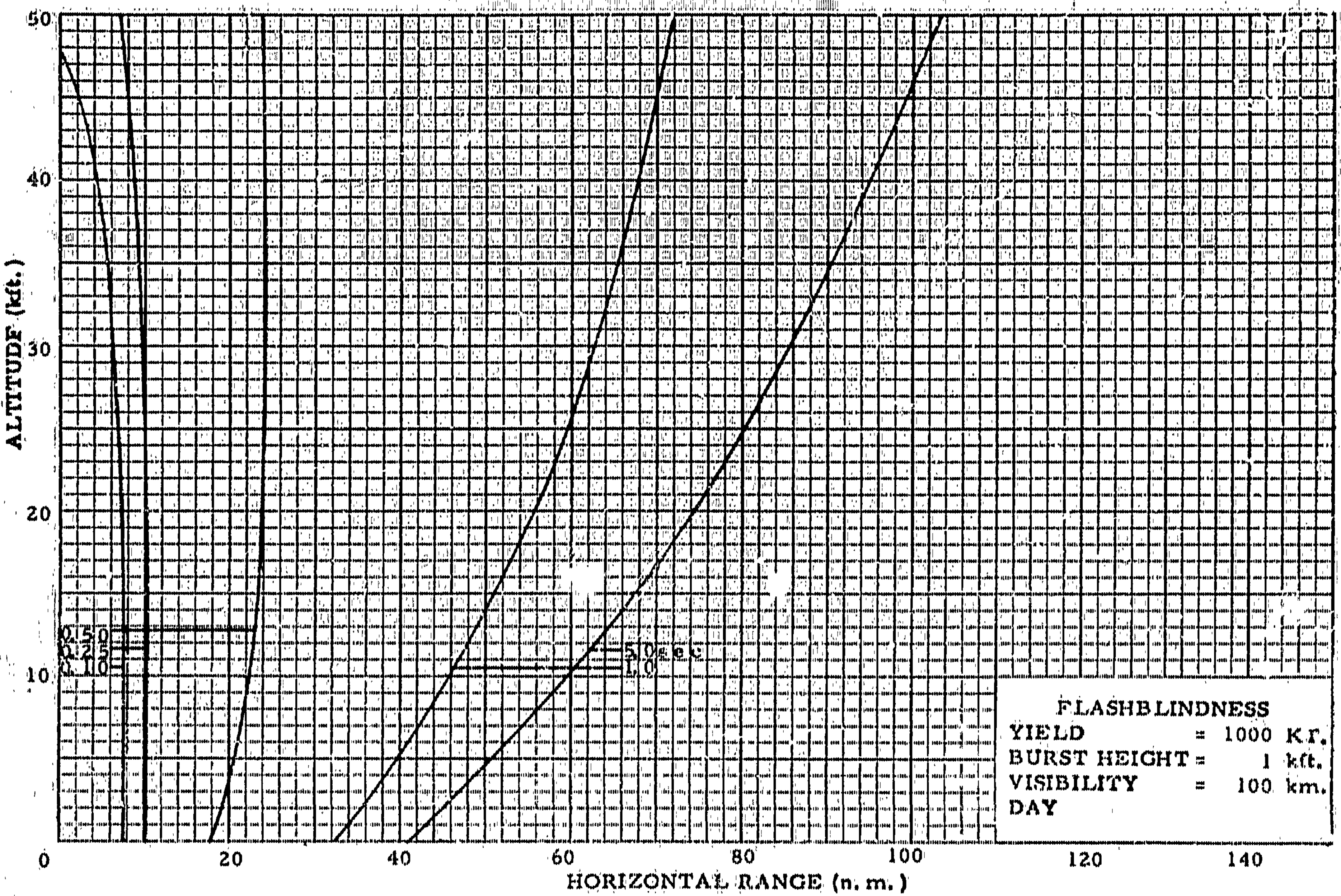
ALTITUDE (kft.)
50
40
30
20
10
0
2
4
6
8
10
12
14
HORIZONTAL RANGE (n. m.)
0.15
0.10
0.50 sec
0.25
0.20
FLASHBLINDNESS
YIELD = 10 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY

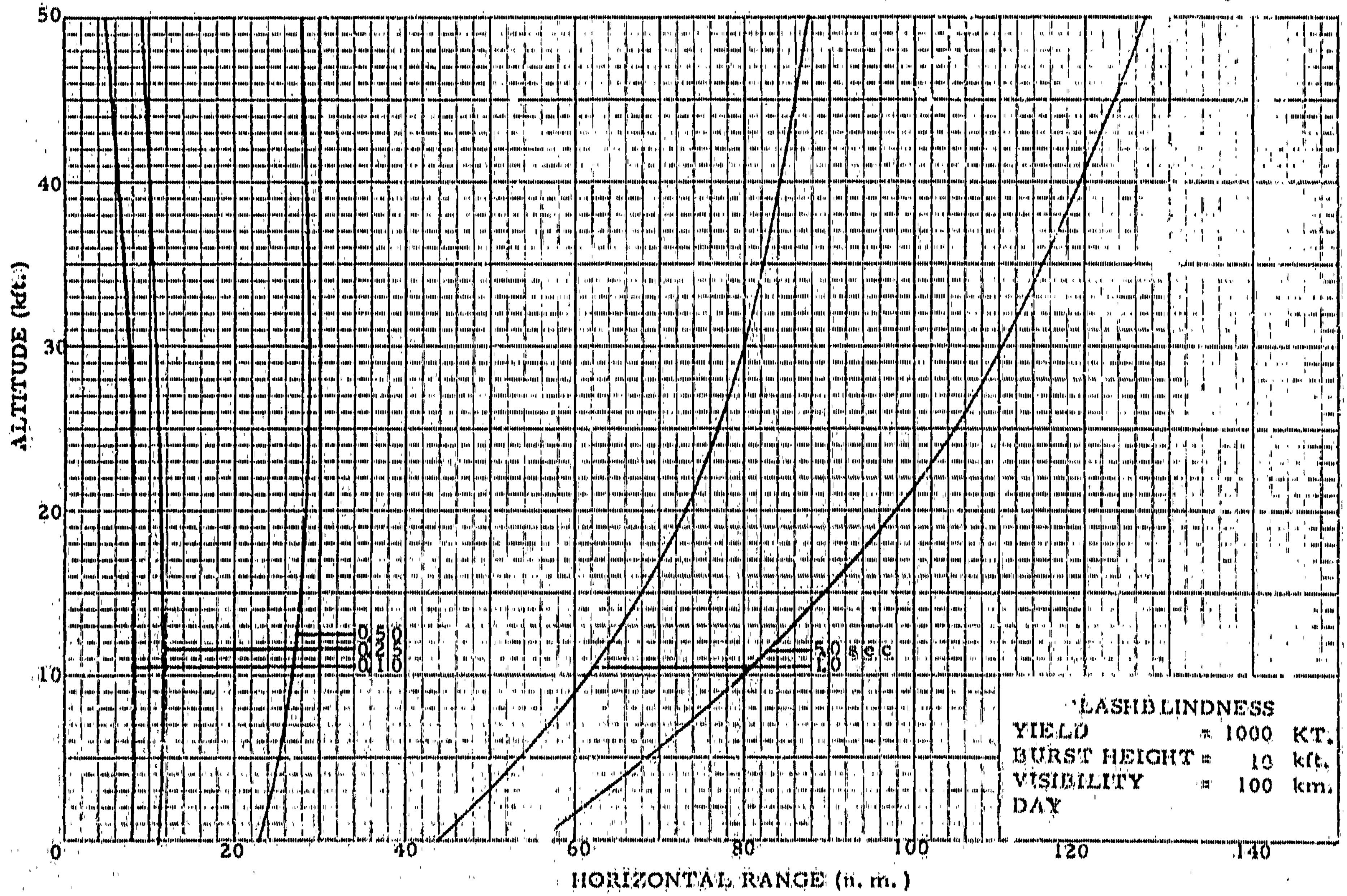

ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70
FLASHBLINDNESS
YIELD = 100 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY


FLASHBLINDNESS
YIELD = 100 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0.25
0.20
0.15
0.10
1.0 sec
0.50
0
10
20
30
40
50
60
70

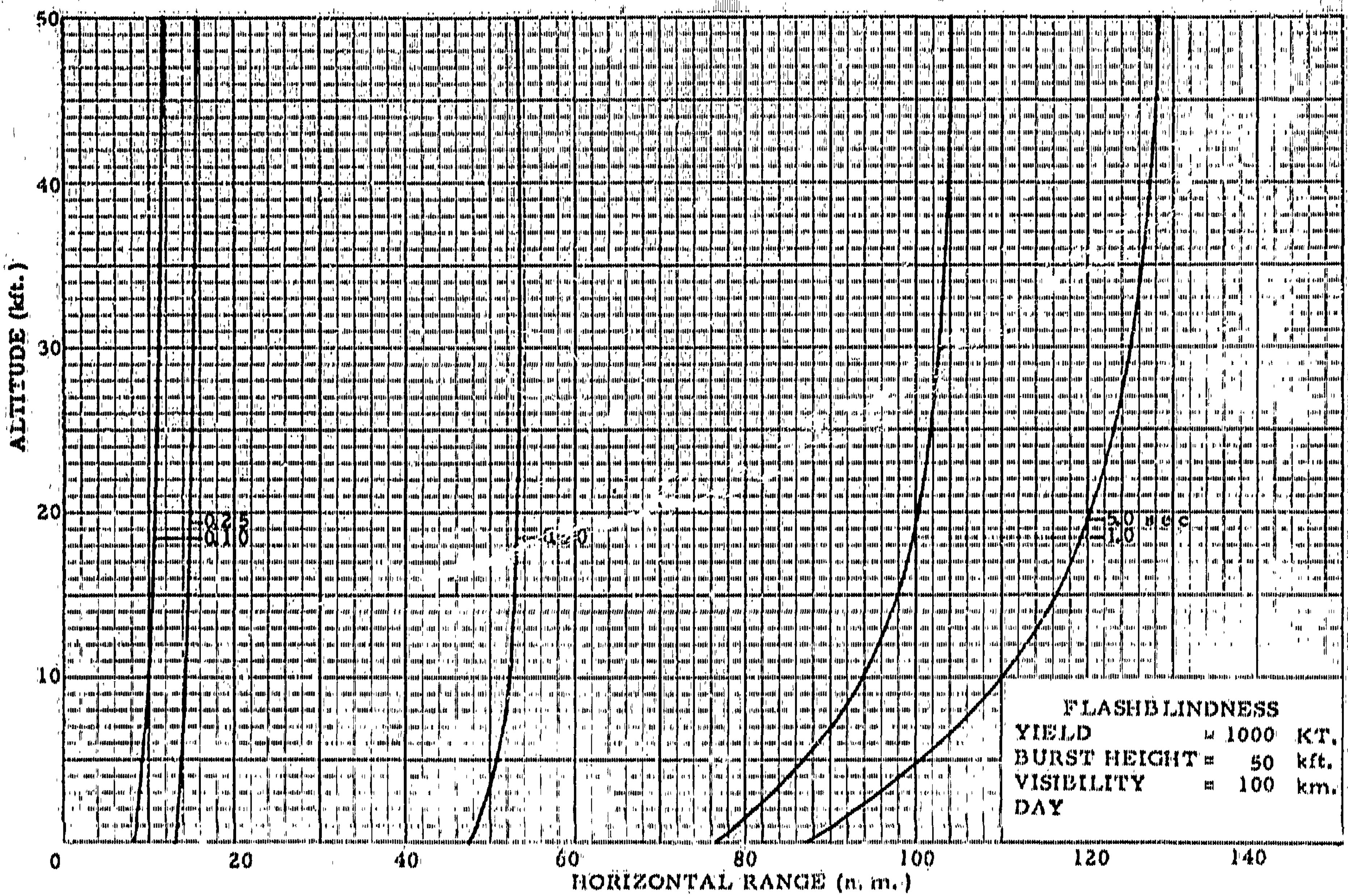


ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70
0.20
0.15
0.10
1.0 sec
0.50
0.25
FLASHBLINDNESS
YIELD = 100 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY

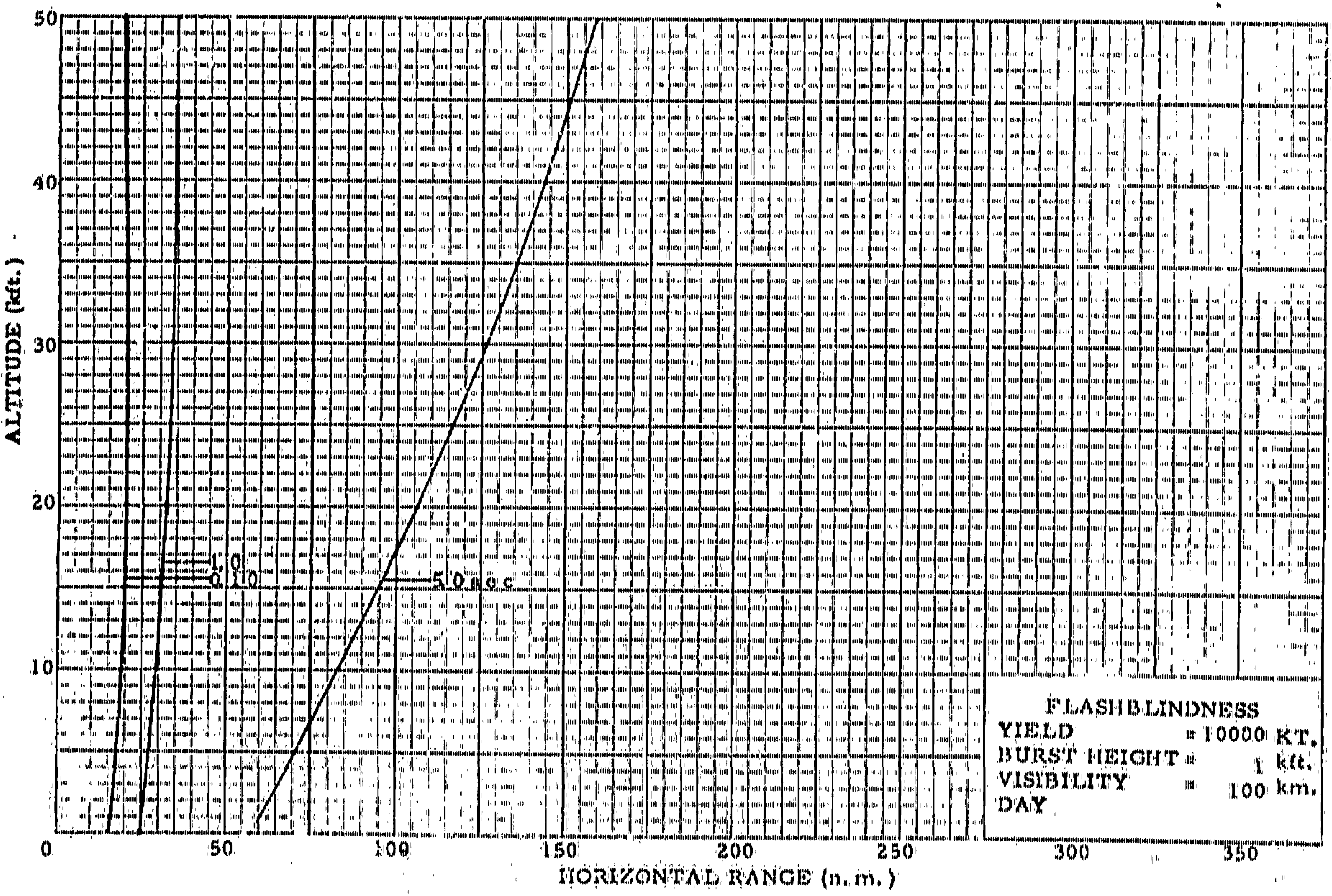

FLASHBLINDNESS
YIELD = 1000 K.T.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY
0.50
0.25
0.10
5.0 sec
1.0
ALTITUDE (kft.)
0
10
20
30
40
50
20
40
60
80
100
120
140
HORIZONTAL RANGE (n. m.)



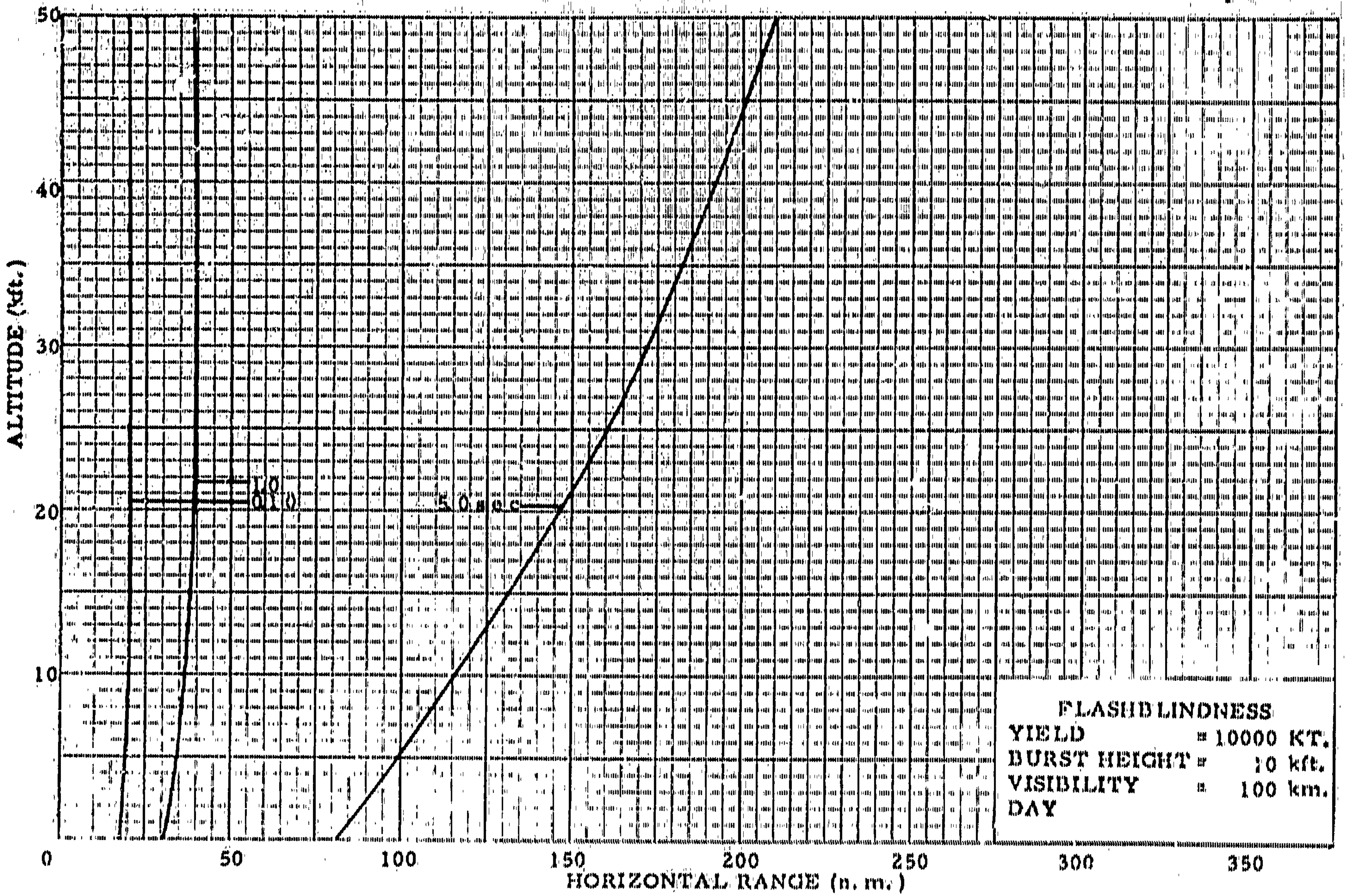
'LASHBLINDNESS
YIELD = 1000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0.50
0.25
0.10
5.0 sec
1.0
0
10
20
30
40
50
0
20
40
60
80
100
120
140

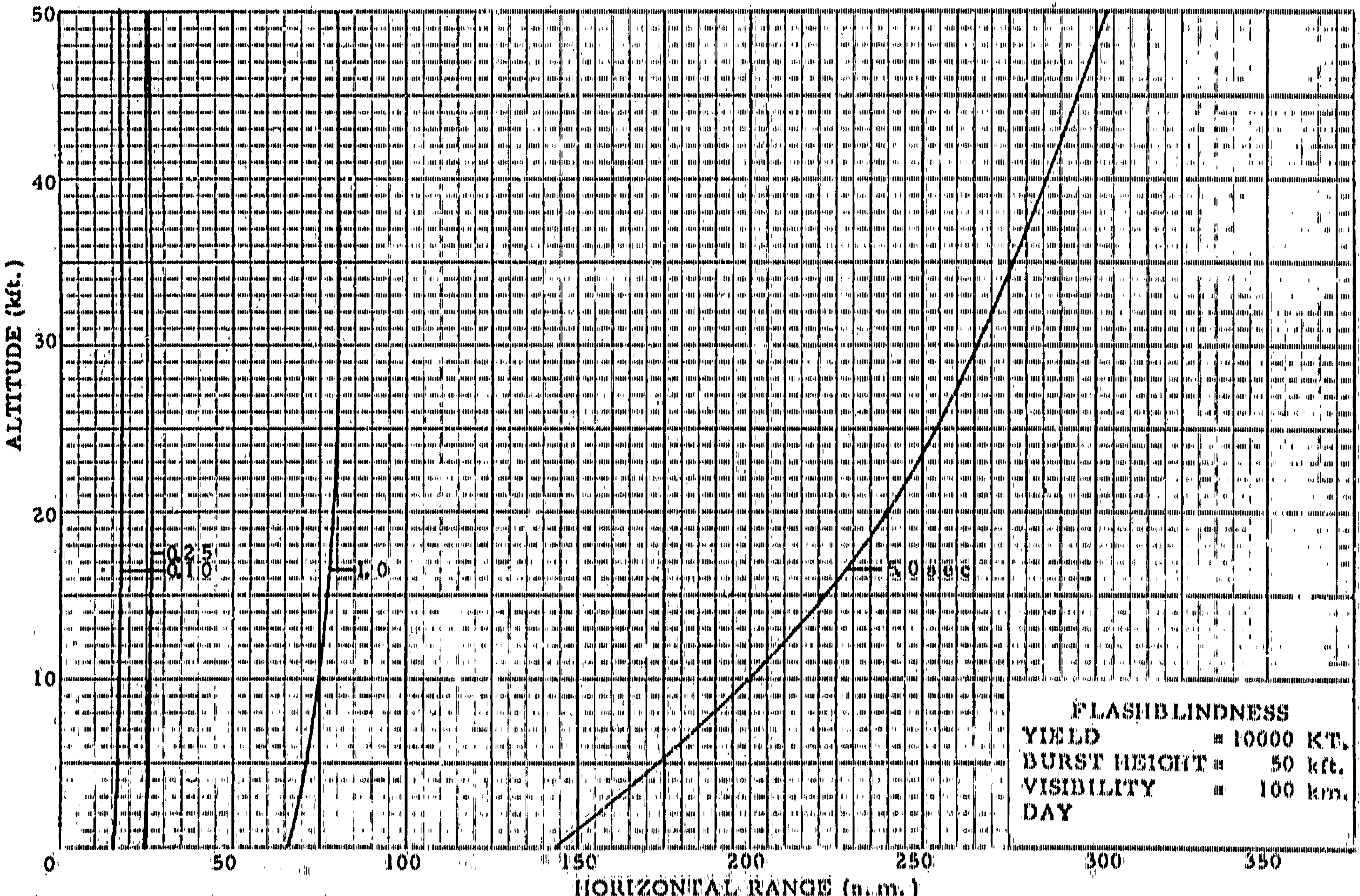


ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
80
100
120
140
0.25
0.10
1.0
5.0 sec
1.0
FLASHBLINDNESS
YIELD = 1000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY

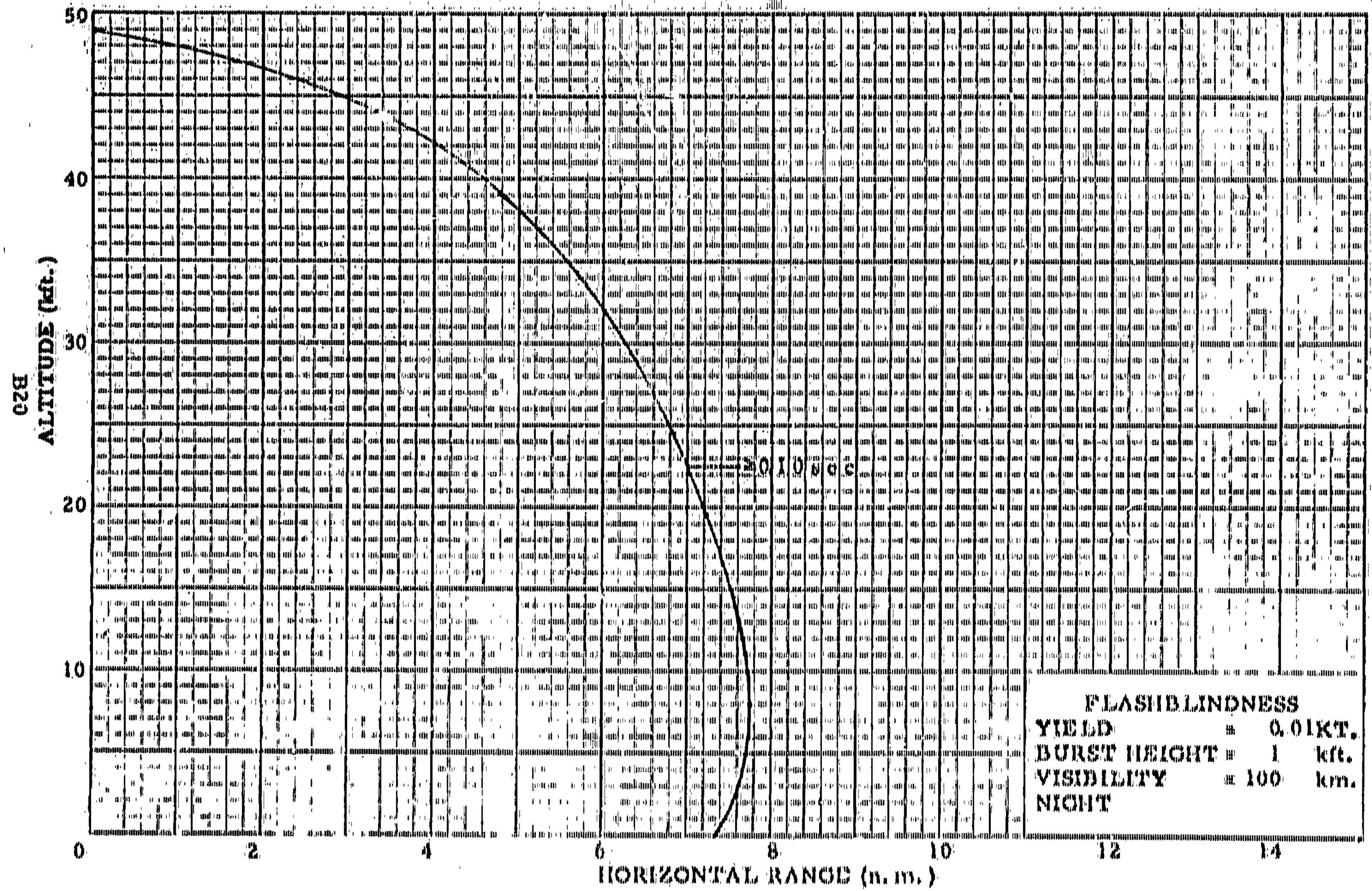


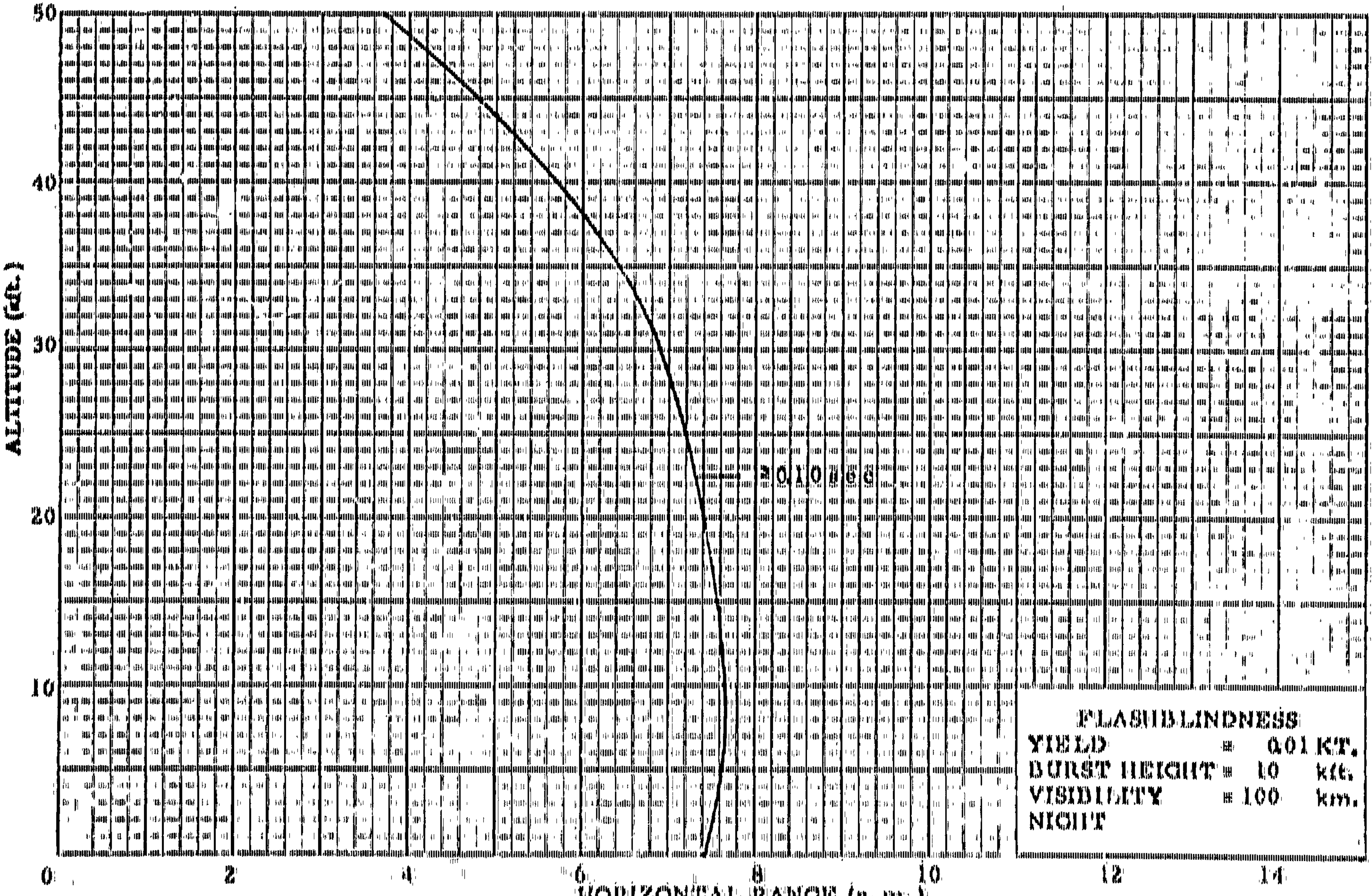
ALTITUDE (kft.)
50
40
30
20
10
0
50
100
150
200
250
300
350
HORIZONTAL RANGE (n.m.)
1.0
0.10
5.0 sec
FLASHBLINDNESS
YIELD = 10000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
DAY


ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
50
100
150
200
250
300
350
10
20
30
40
50
5.0 sec
FLASHBLINDNESS
YIELD = 10000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
DAY

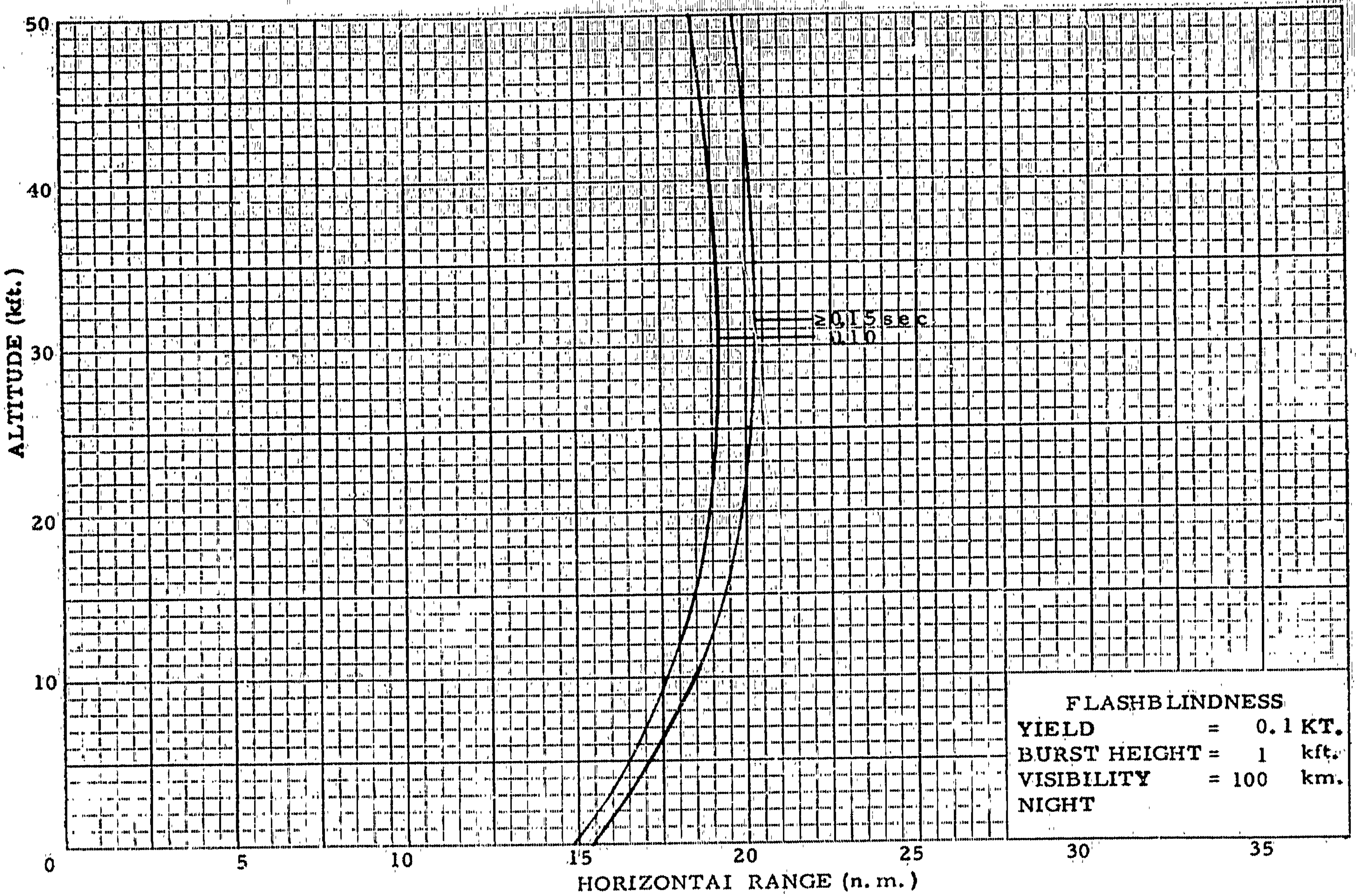


ALTITUDE (kft.)
HORIZONTAL RANGE (n.m.)
0
10
20
30
40
50
100
150
200
250
300
350
0.25
0.10
1.0
5.0 sec
FLASHBLINDNESS
YIELD = 10000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
DAY

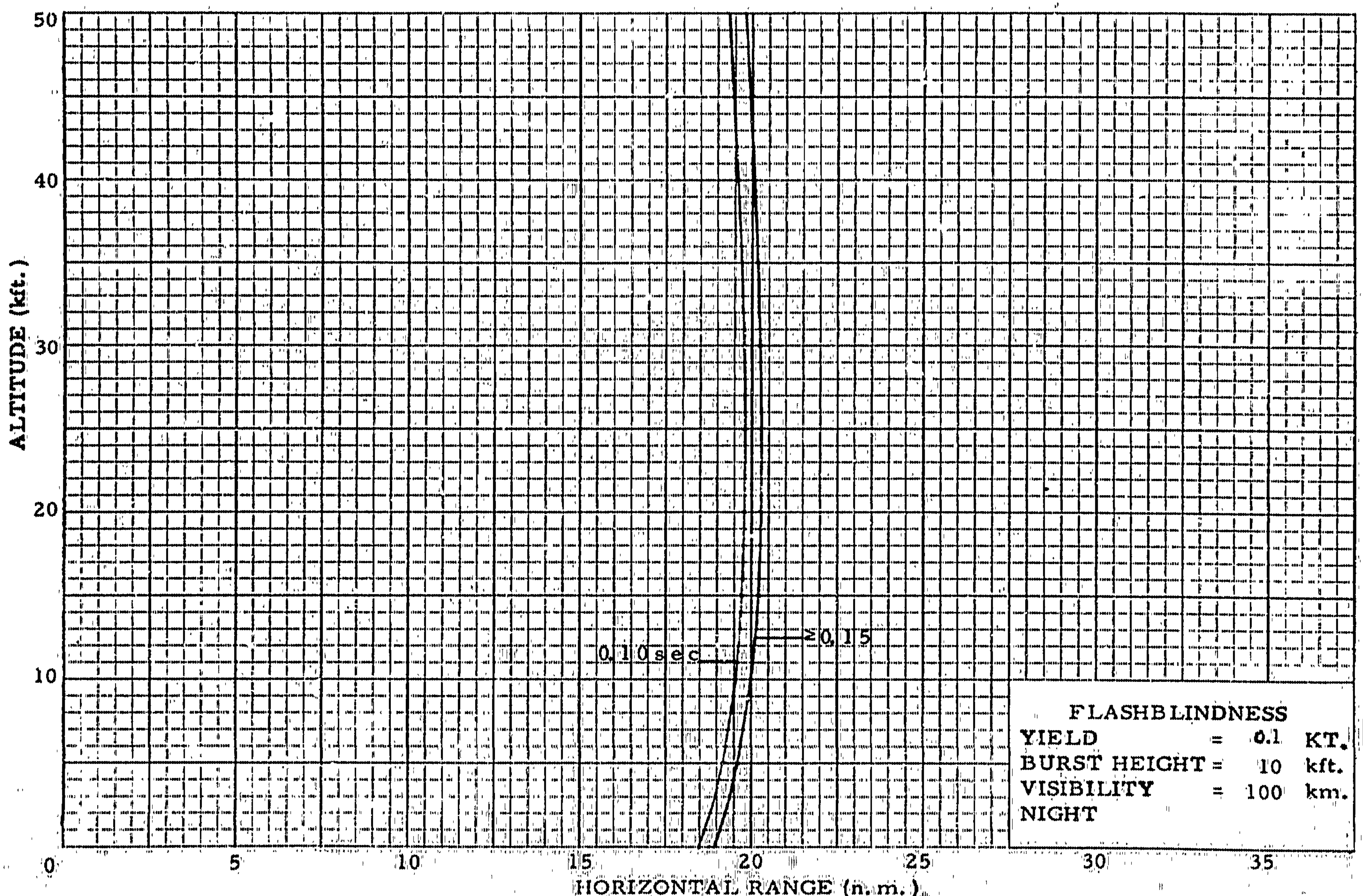

B20
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
2
4
6
8
10
12
14
10
20
30
40
50
FLASHBLINDNESS
YIELD = 0.01KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT

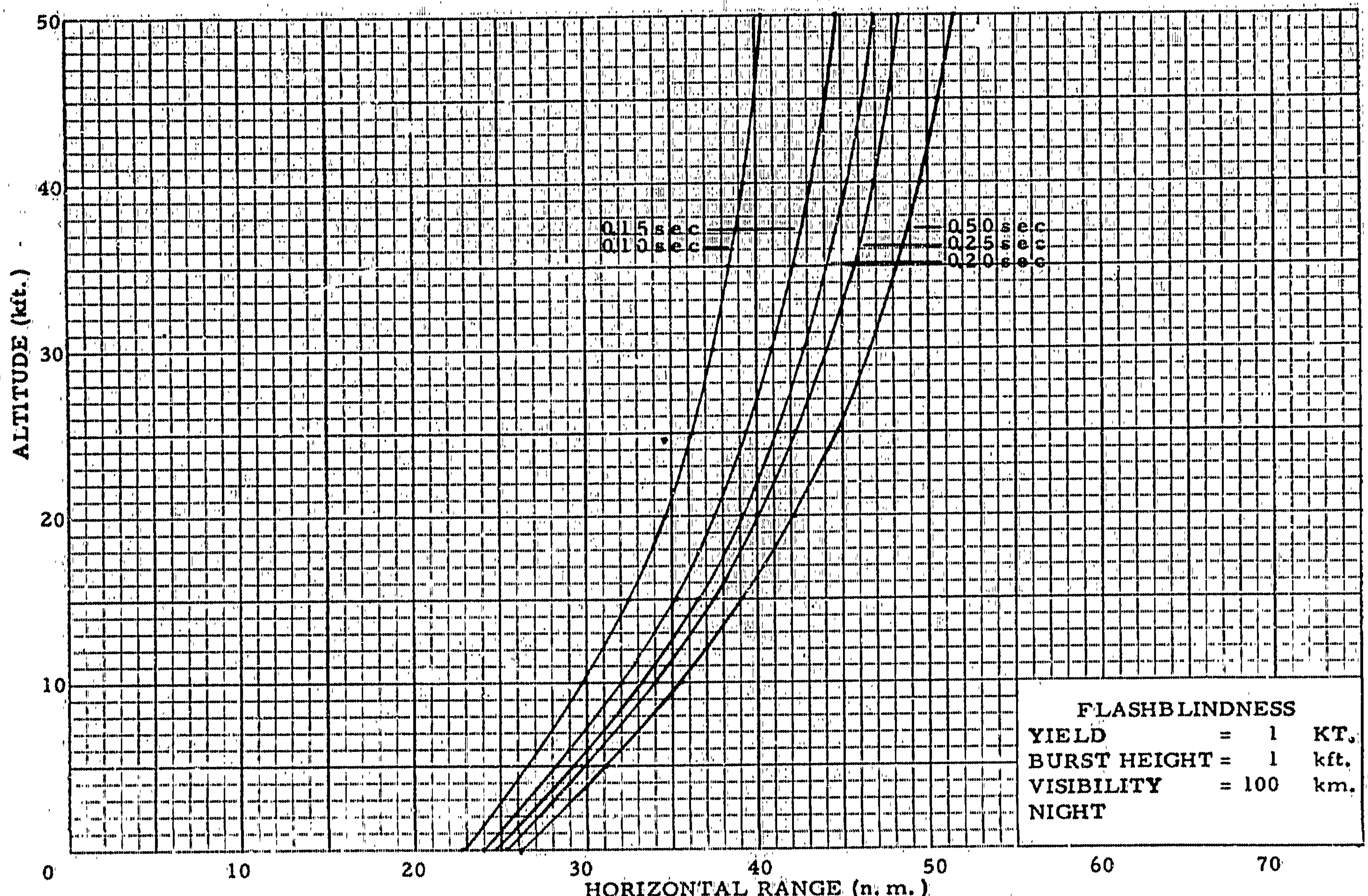


ALTITUDE (kft.)
50
40
30
20
10
0
2
4
6
8
10
12
14
HORIZONTAL RANGE (n.m.)
FLASHBLINDNESS
YIELD = 0.01 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT

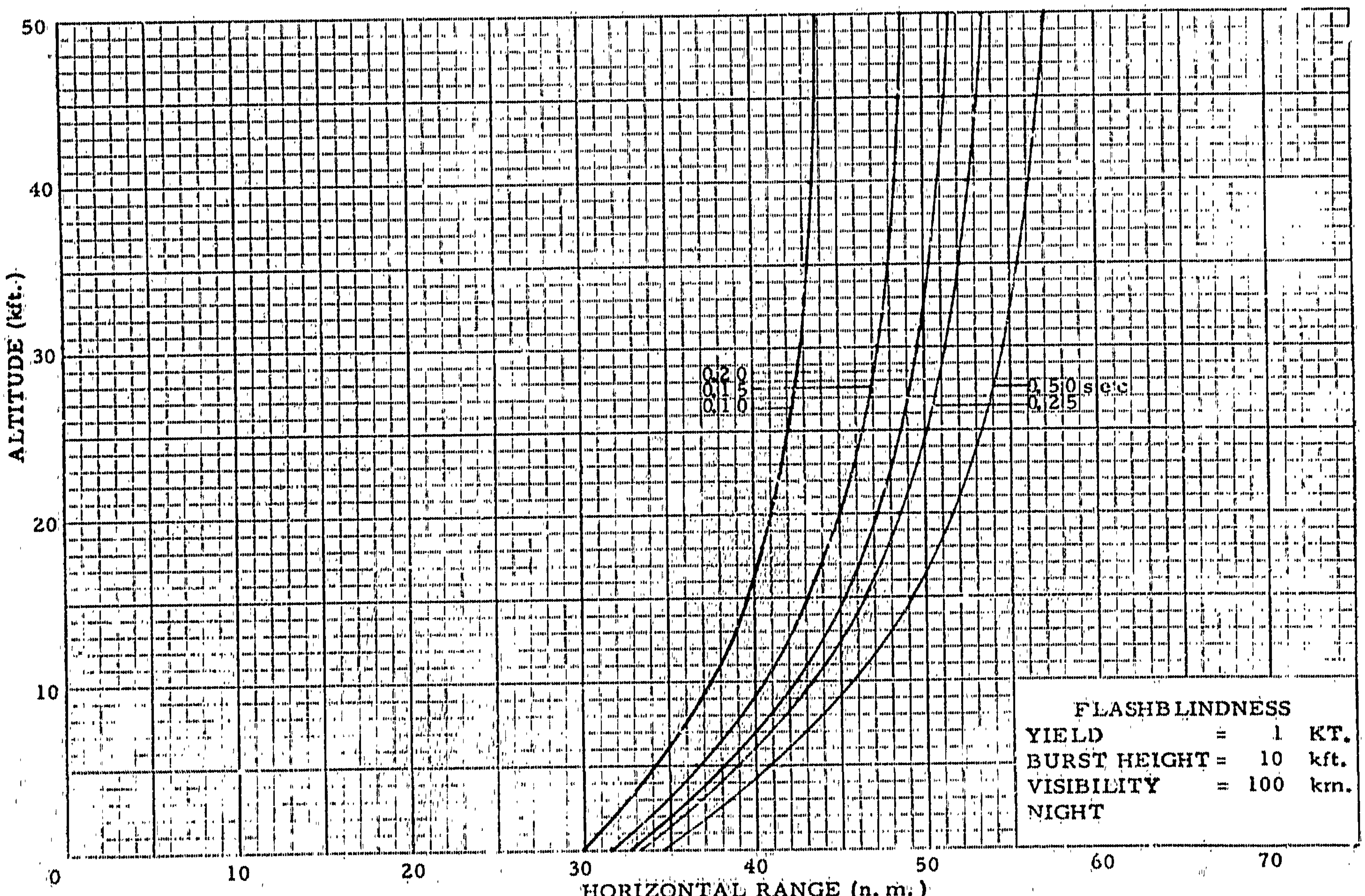


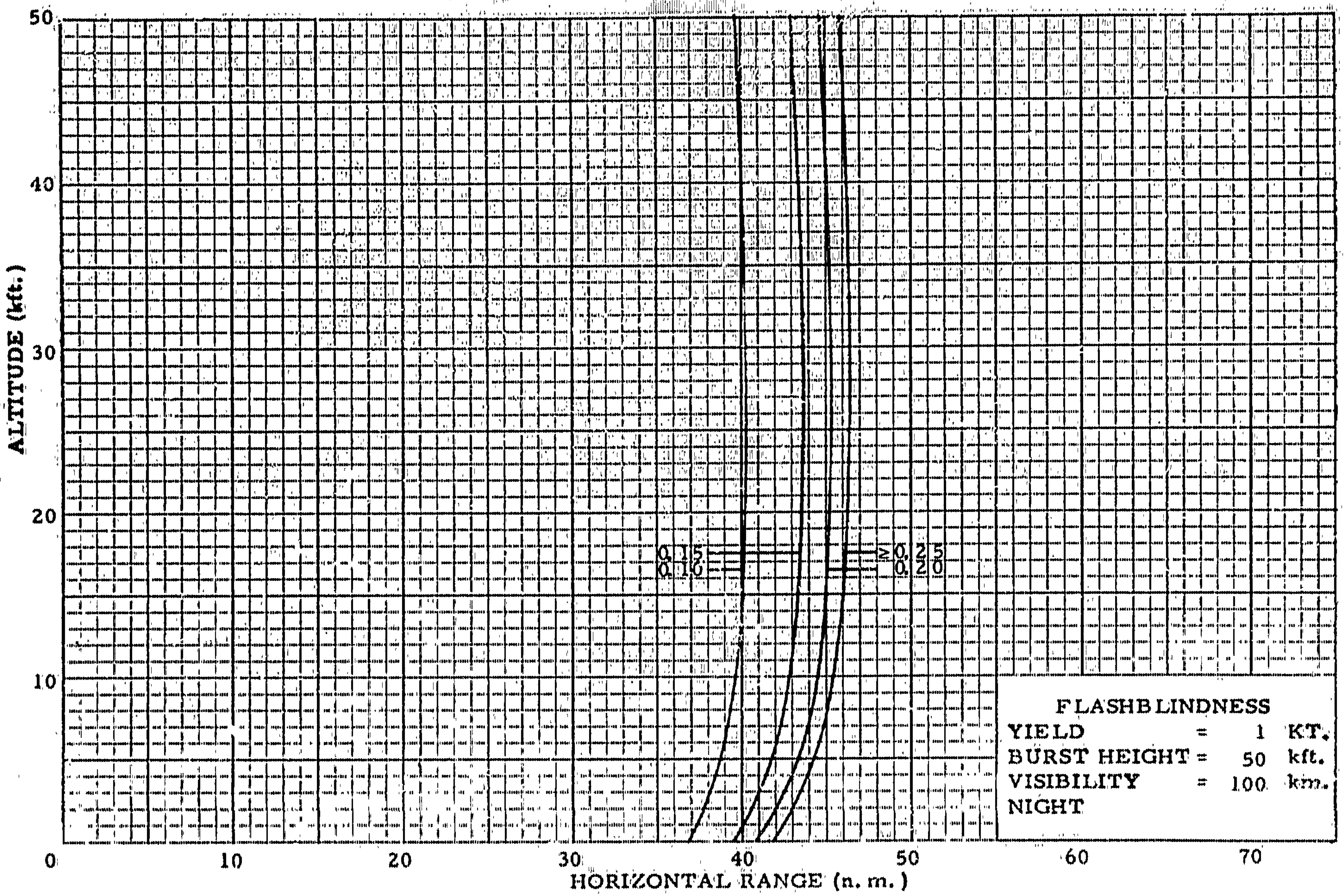
≥0.15 sec
0.10
FLASHBLINDNESS
YIELD = 0.1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAI RANGE (n. m.)
0
5
10
15
20
25
30
35
10
20
30
40
50

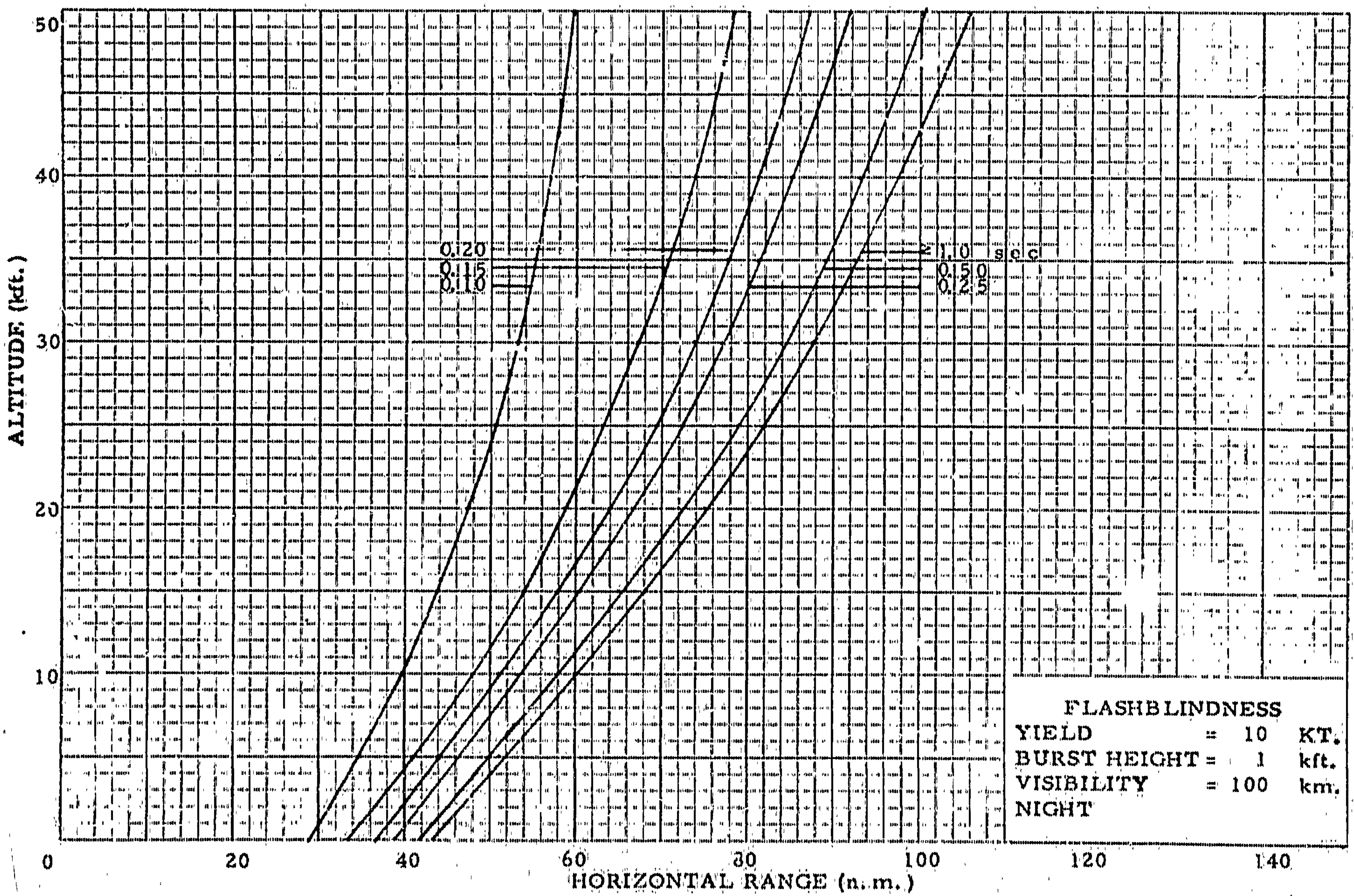

ALTITUDE (kft.)
50
40
30
20
10
0
5
10
15
20
25
30
35
HORIZONTAL RANGE (n.m.)
0.10 sec
≥0.15
FLASHBLINDNESS
YIELD = 0.1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT



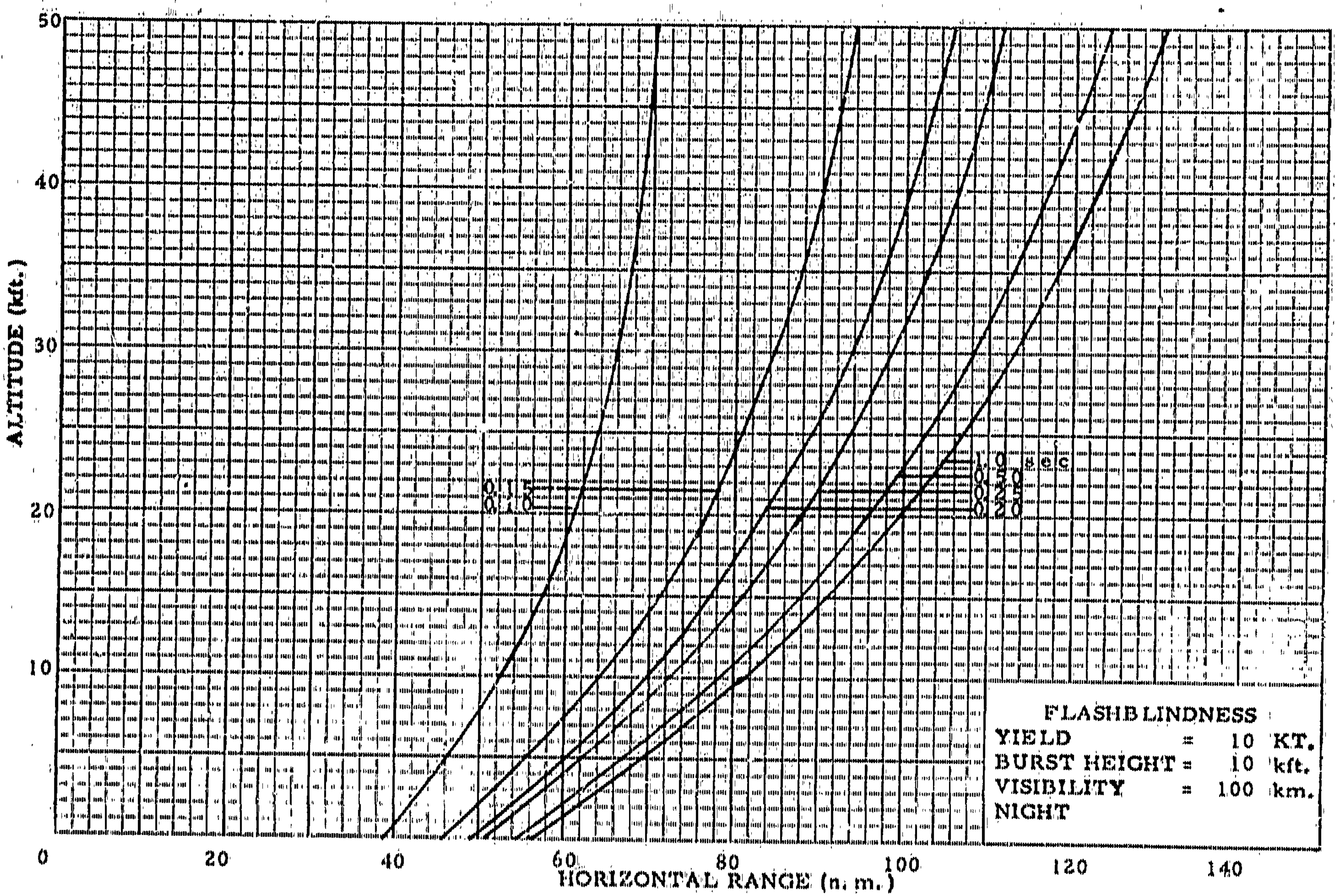
FLASHBLINDNESS
YIELD = 1 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT
0.15 sec
0.10 sec
0.50 sec
0.25 sec
0.20 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)

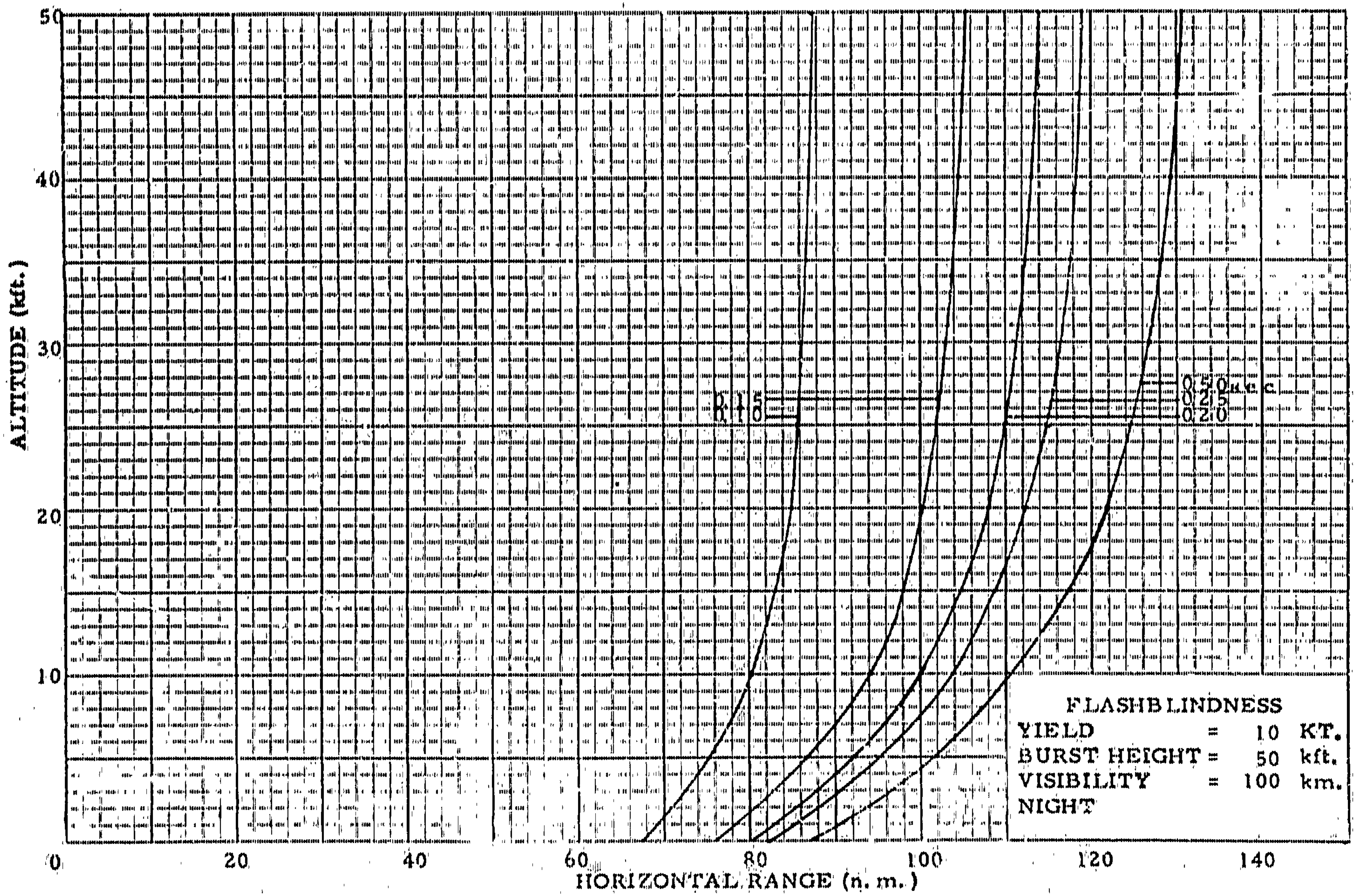

FLASHBLINDNESS
YIELD = 1 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT
0.20
0.15
0.10
0.50 sec
0.25
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70


FLASHBLINDNESS
YIELD = 1 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT
0.15
0.10
≥0.25
0.20
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
60
70



FLASHBLINDNESS
YIELD = 10 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT
0.20
0.15
0.10
1.0 sec
0.50
0.25
ALTITUDE (kft.)
HORIZONTAL RANGE (n.m.)
0
10
20
30
40
50
60
80
100
120
140


ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
30
40
50
0
20
40
60
80
100
120
140
1.0 sec
0.50
0.20
0.15
0.10
FLASHBLINDNESS
YIELD = 10 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT



FLASHBLINDNESS
YIELD = 10 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT
0.50 sec
0.25
0.20
0.15
0.10
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
10
20
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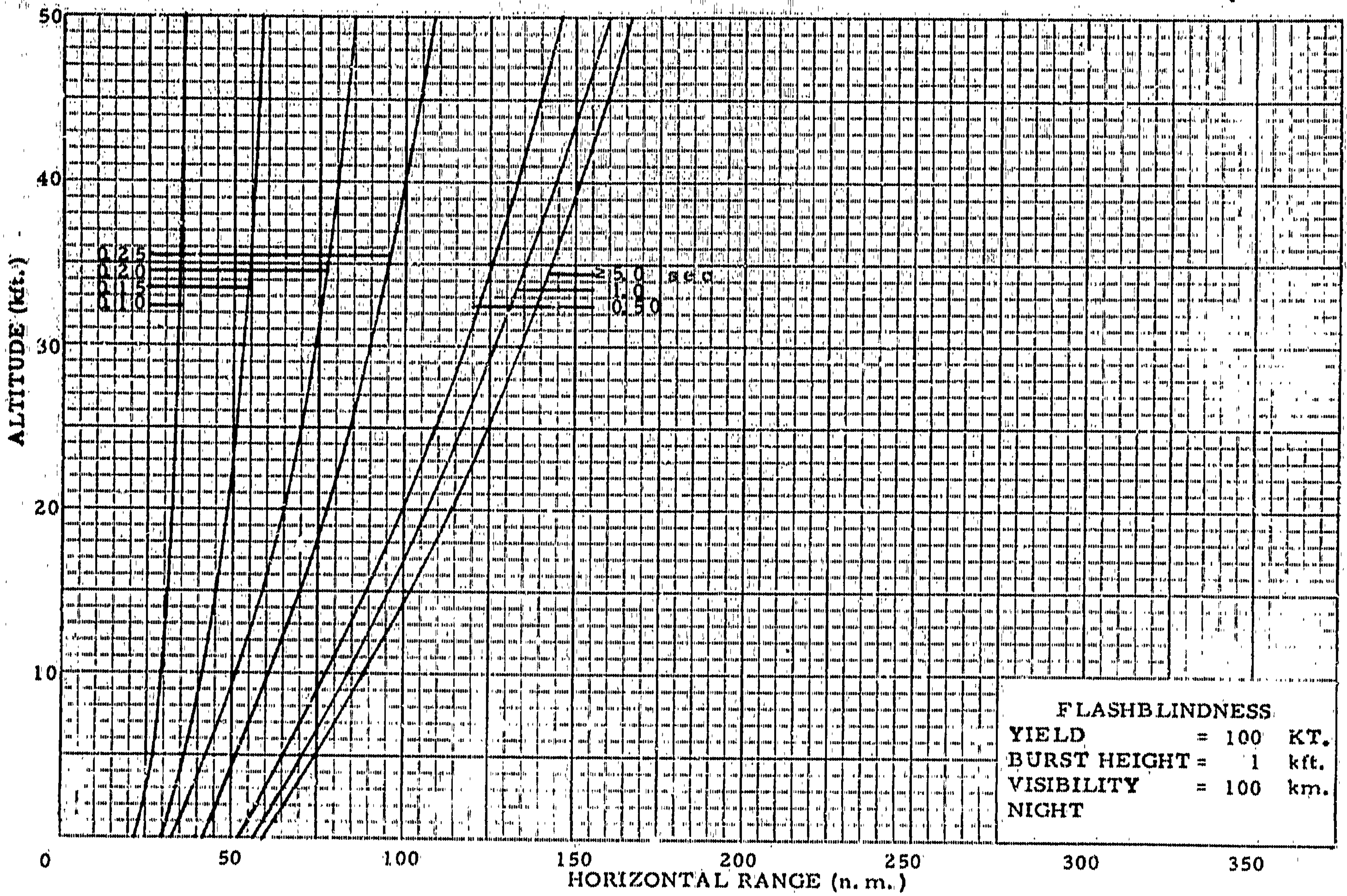

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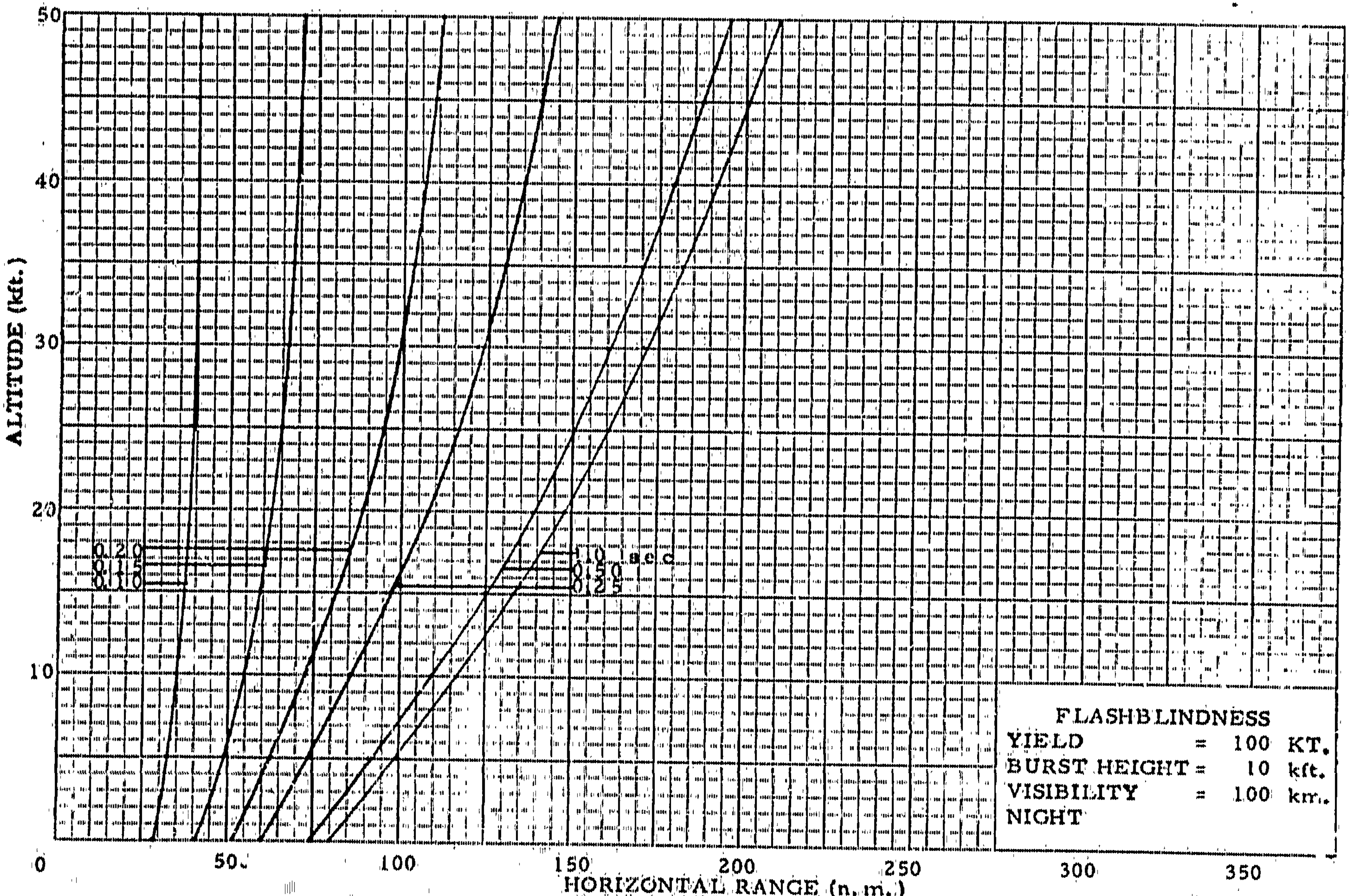
200
250
300
350
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
FLASHBLINDNESS
YIELD = 100 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT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BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT
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1.0 sec
0.50
0.25
ALTITUDE (kft.)
HORIZONTAL RANGE (n.m.)
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150
200
250
300
350
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20
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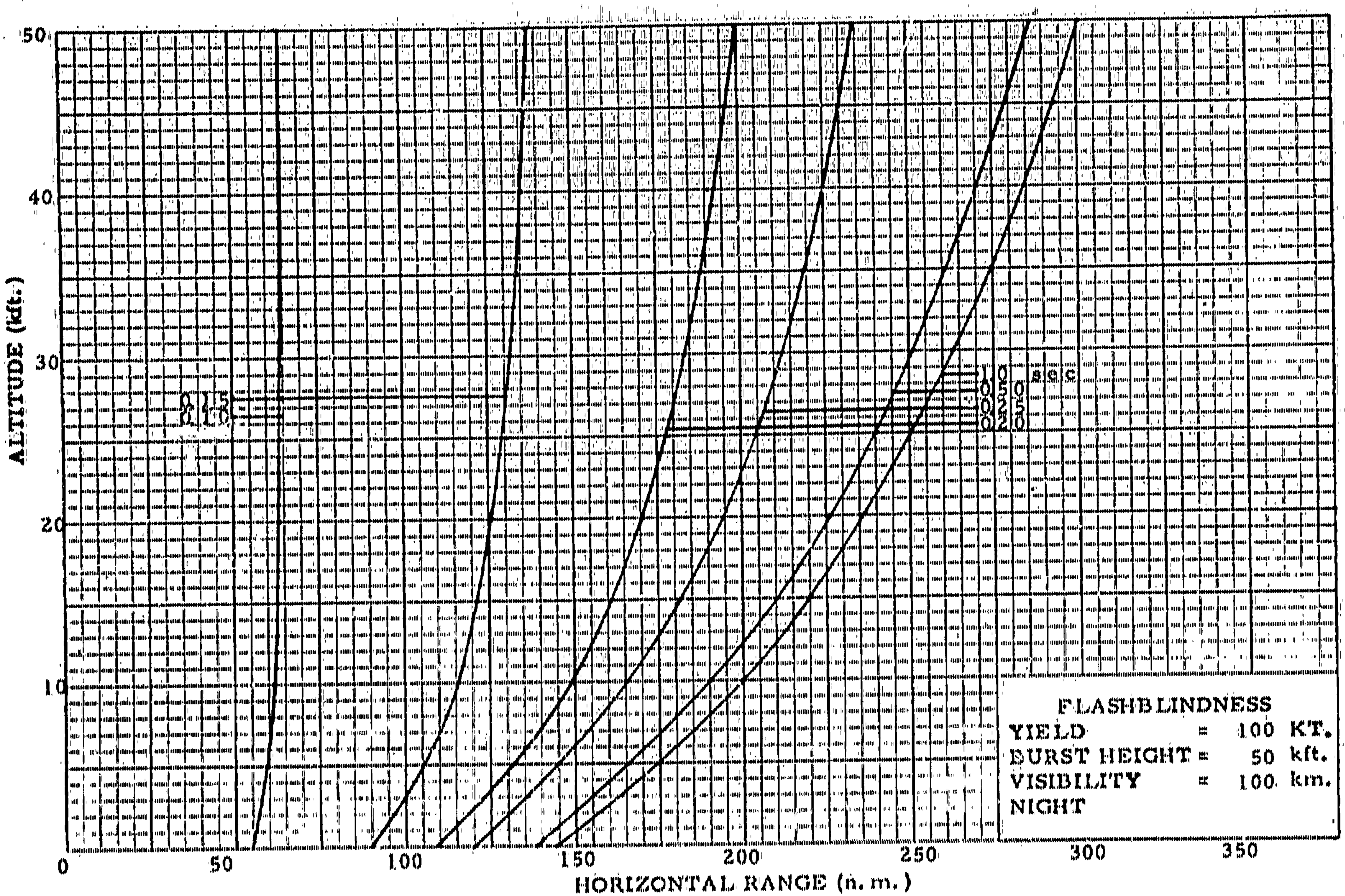
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HORIZONTAL RANGE (n. m.)
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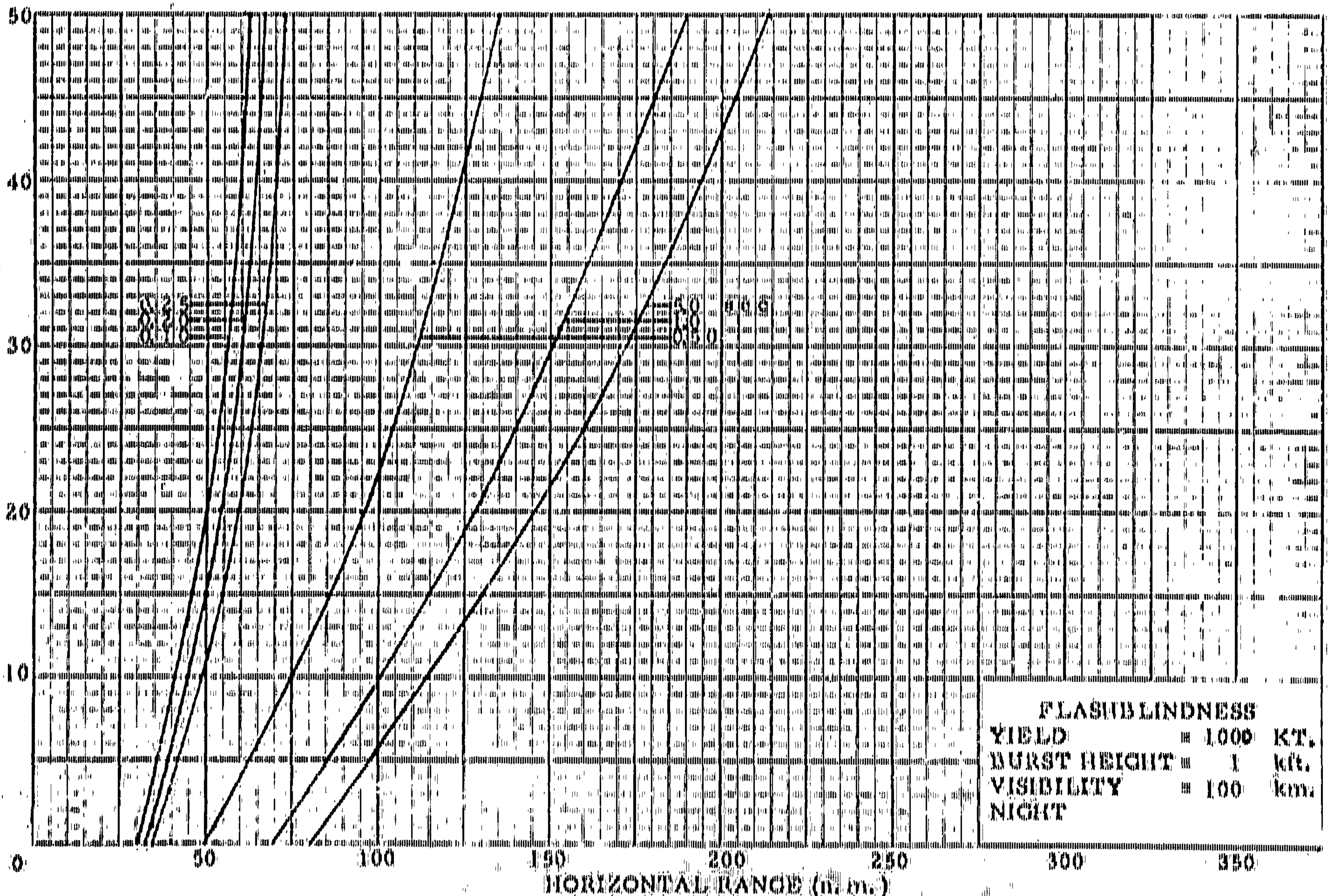
1.0
0.50
0.25
0.20
sec
FLASHBLINDNESS
YIELD = 100 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT

B33


ALTITUDE (kft.)
HORIZONTAL RANGE (n.m.)
FLASHBLINDNESS
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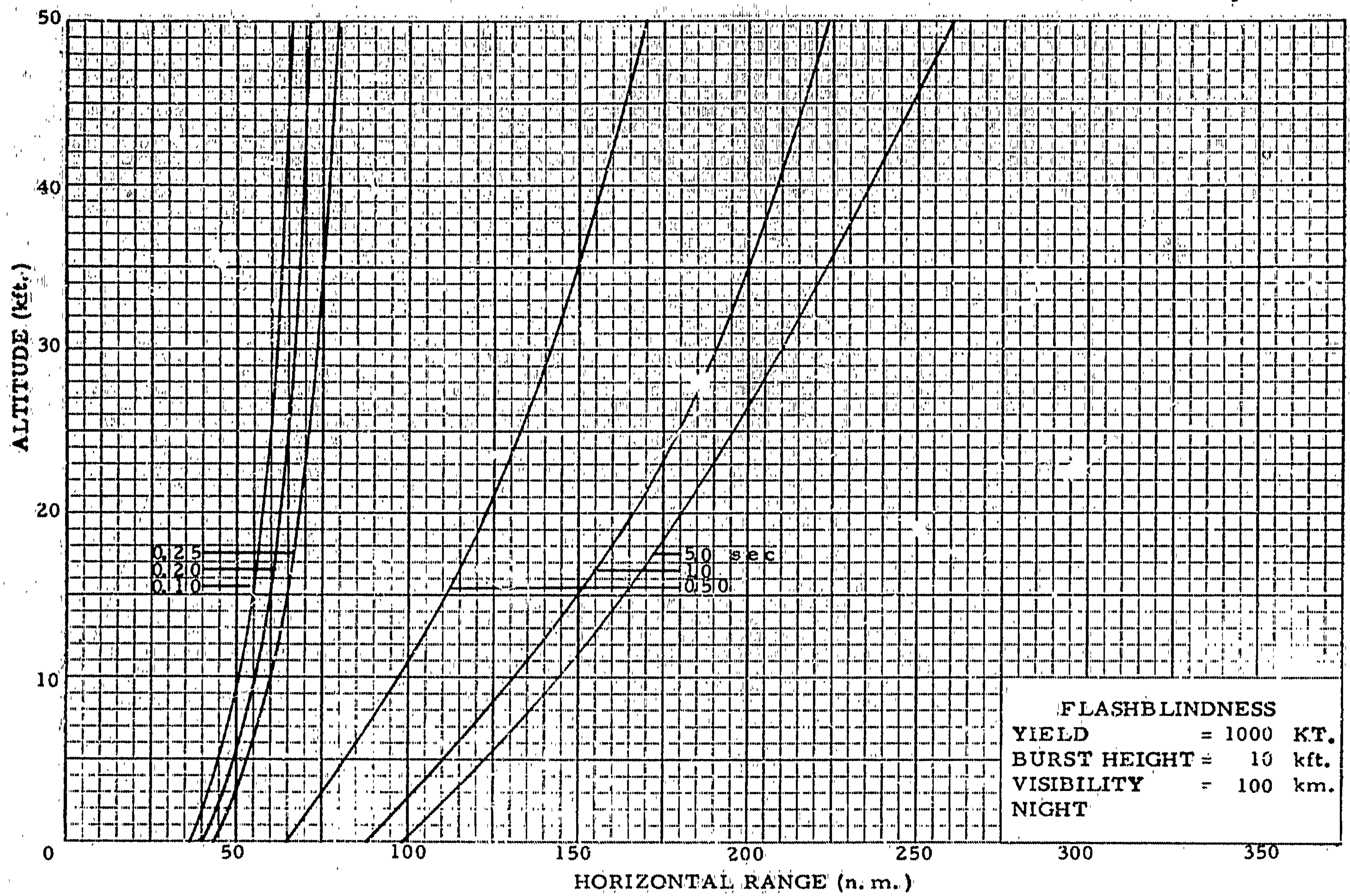
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT



ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0
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100
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0.25
0.20
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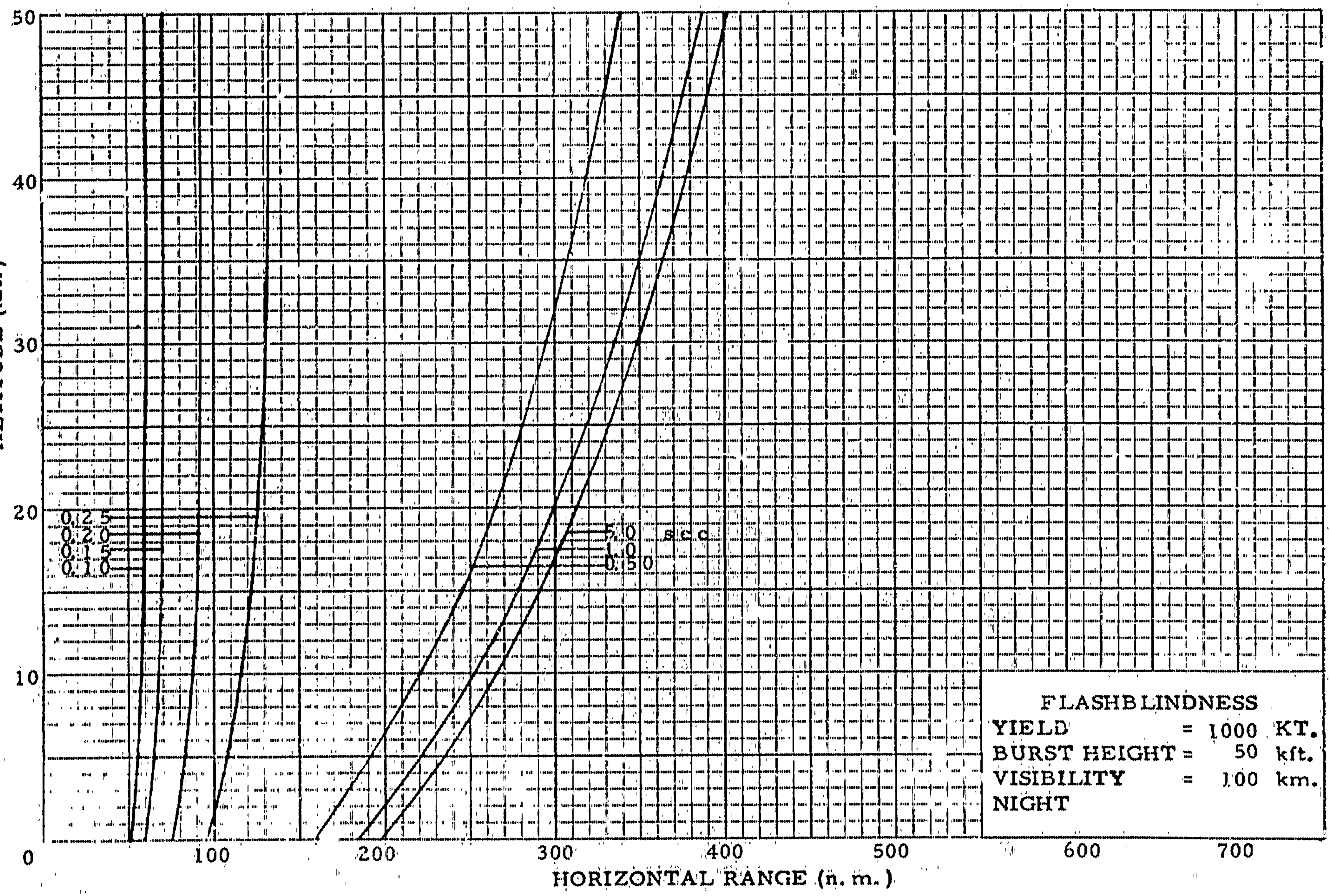
0.50
FLASHBLINDNESS
YIELD = 1000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT


FLASHBLINDNESS
YIELD = 1000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
0.25
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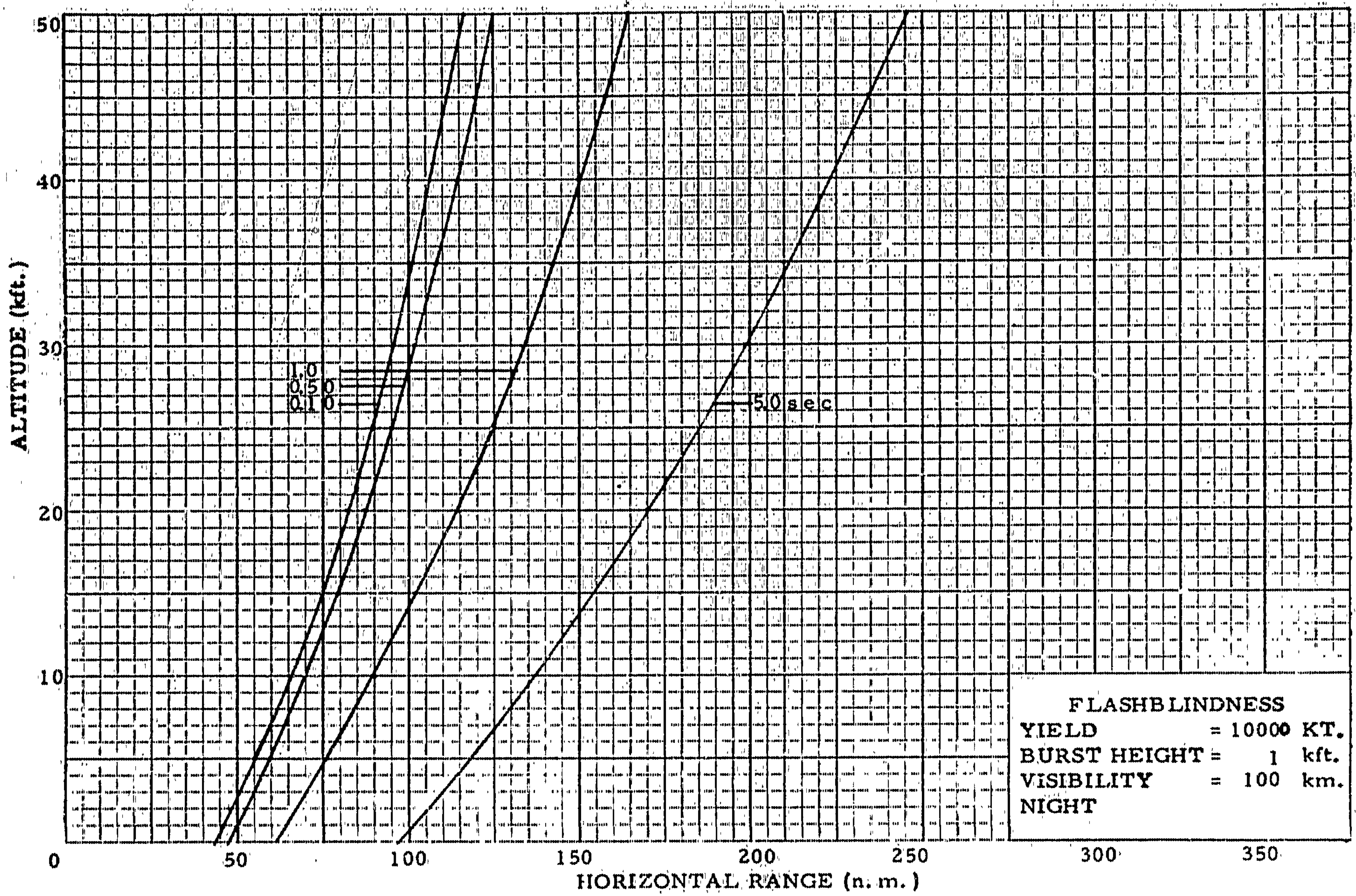
FLASHBLINDNESS
YIELD = 10000 KT.
BURST HEIGHT = 1 kft.
VISIBILITY = 100 km.
NIGHT
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ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
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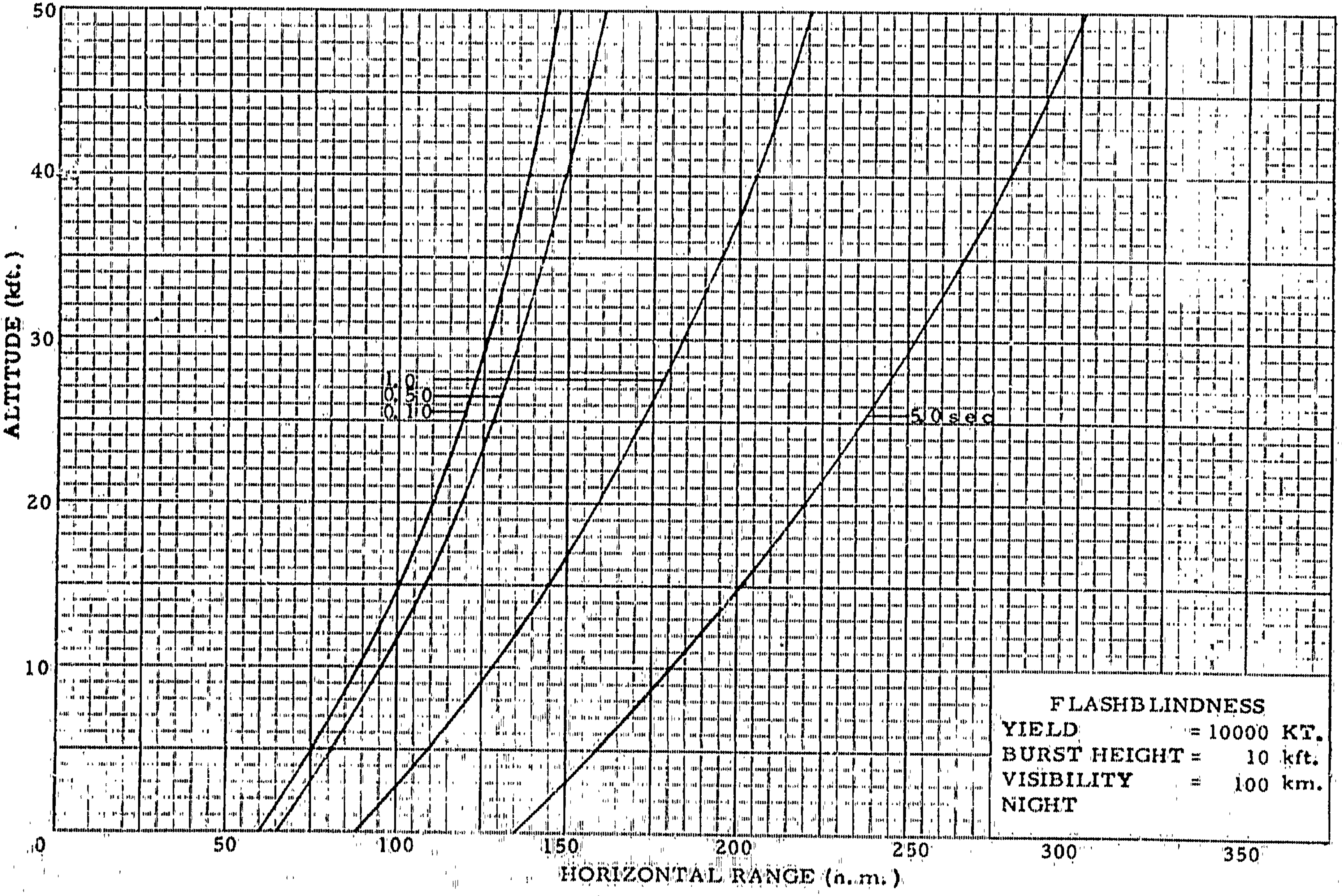
FLASHBLINDNESS
YIELD = 10000 KT.
BURST HEIGHT = 10 kft.
VISIBILITY = 100 km.
NIGHT
1.0
0.50
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5.0 sec
ALTITUDE (kft.)
HORIZONTAL RANGE (n.m.)
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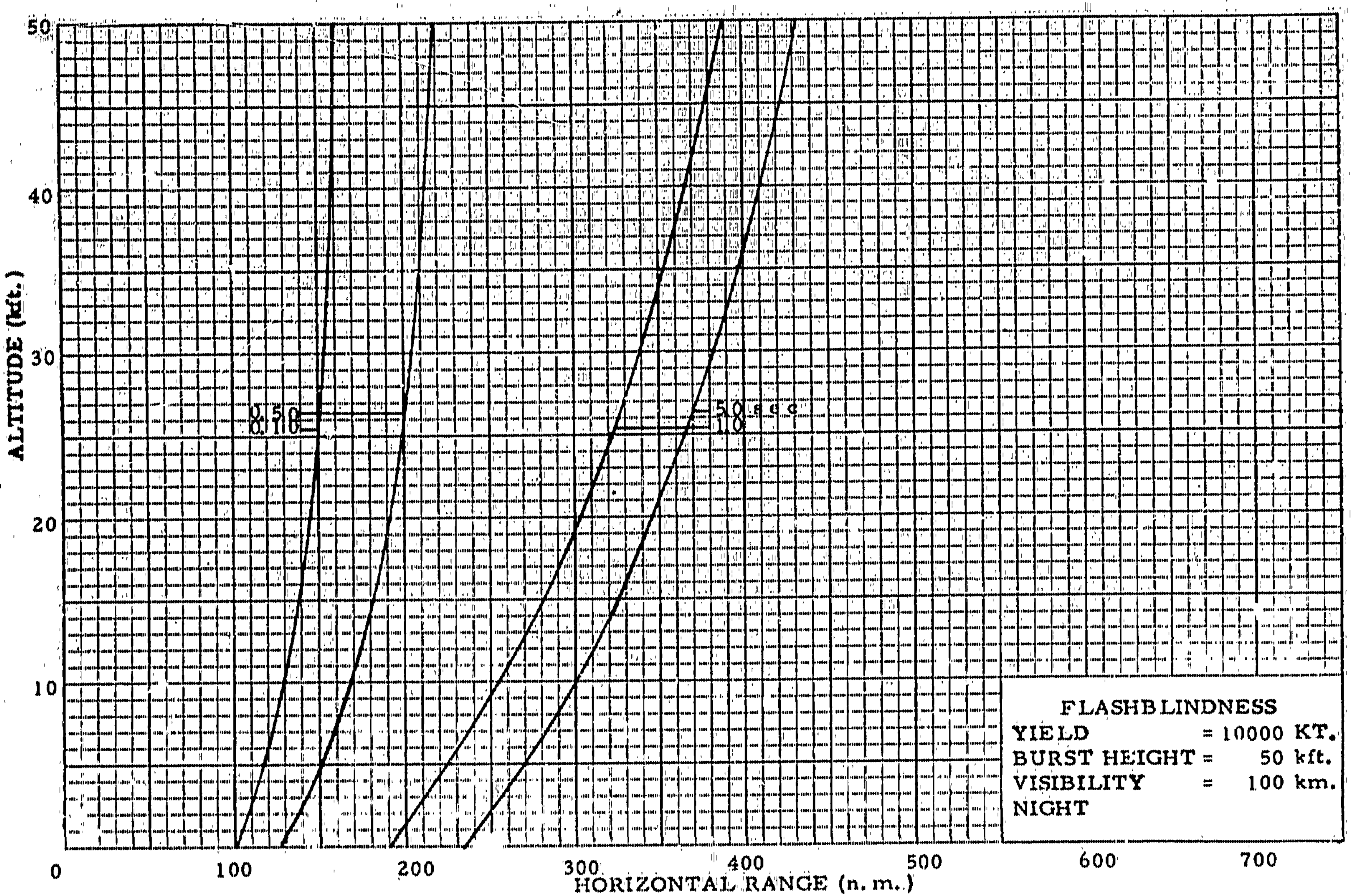
FLASHBLINDNESS
YIELD = 10000 KT.
BURST HEIGHT = 50 kft.
VISIBILITY = 100 km.
NIGHT
ALTITUDE (kft.)
HORIZONTAL RANGE (n. m.)
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13. ABSTRACT

Time and wavelength dependent mathematical models for retinal burns and for flashblindness from nuclear detonations are developed in this report. These models are incorporated into a computer program with the latest weapon and burn threshold data to calculate safe separation distances as a function of time for given sets of initial conditions. The results, which present safe separation envelopes with time as a parameter, are included in the appendices. Yield, altitude of detonation, visibility and day or night conditions are also parameters. Retinal burn predictions with this model compare favorably with the experimental results obtained during Operation Dominic.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Retinal burns; flashblindness; visual effects safe separation distances; nuclear weapons effects; thermal energy from nuclear weapons; retinal burn threshold data; Dominic weapon data; thermal power scaled with yield, burst height and wavelength; nuclear fireball diameter scaled with time, yield, and burst height; time scaled with yield and burst height						

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